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Corrosion Mitigation in Civil Works Projects
December 1979

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CATHODIC PROTECTION OF CIVIL WORKS STRUCTURES

by
A. Kumar
R. Lampo
F. Kearney

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This report lists various design considerations for cathodic protection systems and provides several examples of such systems. It also contains the results of field surveys of U.S. Army Corps of Engineers (CE) installations which have used or are using cathodic protection on hydraulic structures. These surveys indicate that (1) graphite slab anodes can be softened by oxygen attack, (2) unprotected sausage anodes are often damaged by river debris, and (3) button anodes resist river debris and ice damage; button anodes examined during the survey were found to have performed well over a period of 7 years.

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In addition, it was determined that the current requirement for cathodic protection of 1 sq ft (0.092 m^2) of bare steel in aerated water is 2 mA/sq ft (22 mA/m^2). However, since cathodic protection current increases with water velocity, a square root dependence was measured using a cylindrical specimen rotating at a surface velocity of up to 4 ft/s (1.2 m/s).

Finally, it was determined that platinized anodes have a good potential for application in impressed-current cathodic protection systems.

FOREWORD

This study was conducted for the Directorate of Civil Works, Office of the Chief of Engineers (OCE), under CWIS 31204 (Corrosion Mitigation in Civil Works Projects). The OCE Technical Monitor was Mr. J. Robertson. The research was conducted by the Engineering and Materials (EM) Division, U.S. Army Construction Engineering Research Laboratory (CERL). Dr. G. R. Williamson is Chief of EM.

COL L. J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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3

TABLES

FIGURES

FIGURES (cont'd)

7

FIGURES (cont'd)

CATHODIC PROTECTION OF CIVIL WORKS STRUCTURES

1 INTRODUCTION

Background

Cathodic protection has been used since 1824, when it was introduced by Sir Humphrey Davy as a way to protect copper sheathing in ships.[1] More recently, cathodic protection has been used by the U.S. Army Corps of Engineers (CE) on lock gates on the Mississippi River to extend the effective life of paint coatings and to provide supplemental protection to defects in the paint film on immersed steel surfaces. The paint film, which is a hydraulic structure's primary protection against corrosion, is never perfect—defects and holidays are always present, and hard-to-paint areas such as edges, rivet heads, and weld beads may never receive adequate paint protection. In addition, paint film is scratched by debris and barge traffic on the waterways; the exposed steel then corrodes until repainted or repaired.

The first CE cathodic protection systems, introduced in the 1950s, were experimental in nature. At present, cathodic protection is being used on all the new lock gates on the Tennessee Tombigbee Waterway; some of the older gates on the Columbia River in the North Pacific Division (NPD) are being retrofit with impressed-current cathodic protection systems; and new locks on the Red River (Arkansas) are being designed with sacrificial cathodic protection systems.

Objective

The objective of this report is to document the results of a study to: (1) evaluate and improve the existing cathodic protection systems on hydraulic structures, (2) determine the effect of velocity on cathodic protection current requirements, (3) determine the feasibility of using platinized anodes.

Approach

Field surveys were conducted to evaluate the success of cathodic protection systems in CE hydraulic structures. Based on field investigations, general de-

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[1] H. Davy, "On the Corrosion of Copper Sheeting in Seawater and Methods of Preventing This Effect," *Philosophical Transactions,* Vol 114 (Royal Society, London, 1824), pp 151-158.

sign considerations were developed, factors which are important in design were determined, and anode characteristics under actual operating conditions were observed.

Furthermore, laboratory experiments were conducted to determine the effect of aeration, stagnation, and velocity on cathodic protection current requirements for bare steel in water. In addition, the effects of water velocity were simulated in the laboratory by rotating a cylindrical specimen in water; these velocity effects are needed for proper design of cathodic protection systems for hydraulic structures in CE waterways.

The feasibility of using platinized anodes in CE hydraulic structures also was investigated. Current densities most likely to be encountered in the field were applied to platinized titanium in laboratory experiments. Defects were introduced in platinized rods, and the pitting behavior was investigated in the laboratory.

Mode of Technology Transfer

This study will impact the proposed CE guide specification for cathodic protection of hydraulic structures and may impact revisions of Technical Manual (TM) 5-811-4, *Electrical Design, Corrosion Control.*

2 DESIGN CONSIDERATIONS AND EXAMPLES OF CATHODIC PROTECTION SYSTEMS FOR HYDRAULIC STRUCTURES

General

Most hydraulic structures are dewatered only every 10 to 15 years (Figure 1) to inspect seals (Figure 2), pintels (Figure 3), and for general inspection and re-painting (if necessary). Cathodic protection can provide supplemental protection to inadequately painted and/or scratched areas between dewatering cycles. Cathodic protection provides supplemental protection to paint coatings and thereby extends the life of the coatings. Furthermore, it decreases the time the structure must be out of service during interim inspections and can increase the total life of the structure.

It has been generally observed that the corrosion rate at a flaw on a coated surface is greater than would

be the case on an uncoated surface in the same environ-ment.[2] A lock gate with a hole or weld defect in a critical location is not considered structurally sound; therefore, a lock gate with a corrosion pit in a critical location is considered equally unsound. Furthermore, misalignment can be caused by extensive deterioration of steel near the quoin and/or the miter end.

The design of a cathodic protection system to miti-gate the corrosion of immersed steel in hydraulic structures involves consideration of the following factors:

1. Corrosivity of the water

2. Anode selection

3. Coating selection

4. Condition of the coating

5. Current distribution

6. Resistance of the circuit

7. Structural configuration.

Although the factors listed above are interrelated, they will be discussed separately in the following sections.

Corrosivity of the Water

The corrosivity of the water is the single most im-portant criterion for the design of a cathodic protec-tion system. The corrosivity of water depends on its resistivity, pH, oxygen concentration and hardness.

1. The presence of salts such as chlorides decreases resistivity; chloride ions also act as depolarizers, and the corrosivity of the water is therefore increased.[3]

2. A small decrease in pH (e.g., from 6 to 4) can make water more acidic and extremely corrosive.

3. The concentration of oxygen increases the corro-sion rate of steel in water. Oxygen concentration cells can be set up even in stagnant water. Steel which is less aerated is anodic to regions which are more aerated. Oxygen-poor areas in stagnant water are anodic to oxygen-rich areas near the surface and corrode more rapidly.

4. Another significant factor is water hardness. Hard waters have a tendency to deposit a carbonate scale on the steel surface. This scale acts like a coating and protects the steel. Therefore, soft waters are more corrosive to steel structures than hard waters.

Anode Selection

Magnesium, zinc, or aluminum anodes can be used in sacrificial cathodic protection systems. The charac-teristics of galvanic and impressed-current anodes are shown in Table 1. In waters with resistivity higher than 2500 ohm-cm, aluminum and zinc do not have enough galvanic over-potential, and only magnesium, which has a potential difference of 1.0 V with respect to steel, can be used for steel. The properties of anodes are described in detail in TM 5-811-4.[4]

In brackish waters (resistivity less than 2500 ohm-cm), the consumption rate of magnesium is increased, requiring that the anodes be replaced frequently. For example, some of the locks of the Arkansas River in the Tulsa District have used magnesium slab anodes for cathodic protection of mooring bits, tainter valves, and tainter gates. Because of the low resistivity (2000 ohm-cm) and high velocity water at these installations, the magnesium anodes have to be replaced every 2 to 4 years.

In freshwater (resistivity greater than 3000 ohm-cm), the "throw distance" of magnesium for painted steel is approximately 2 ft (0.069 m), and a large number of anodes are required for complete coverage. In addition, the presence of ice and/or debris makes it imperative that anodes be protected from mechanical damage. Because of these restrictions, the best potential appli-cations are areas which are localized, structurally com-plex, and mechanically enclosed (e.g., intake gates, mooring bits, or tainter valves); sacrificial cathodic protection of these areas by magnesium slabs, rods, and ribbon anodes can be accomplished successfully.

[2]H. H. Uhlig, *Corrosion and Corrosion Control* (John Wiley and Sons, Inc., 1963).

[3]H. H. Uhlig, *Corrosion and Corrosion Control* (John Wiley and Sons., Inc., 1963); M. G. Fontana and N. P. Greene, *Corrosion Engineering* (McGraw-Hill Book Co., 1967); *Recommended Practice for Control of External Corrosion*, RP-01-69 (National Association of Corrosion Engineers [NACE] Standard, 1969); and L. M. Applegate, *Cathodic Protection* (McGraw-Hill Book Co., 1960).

[4]*Electrical Design, Corrosion Control*, Technical Manual (TM) 5-811-4 (Department of the Army, 1 August 1962).
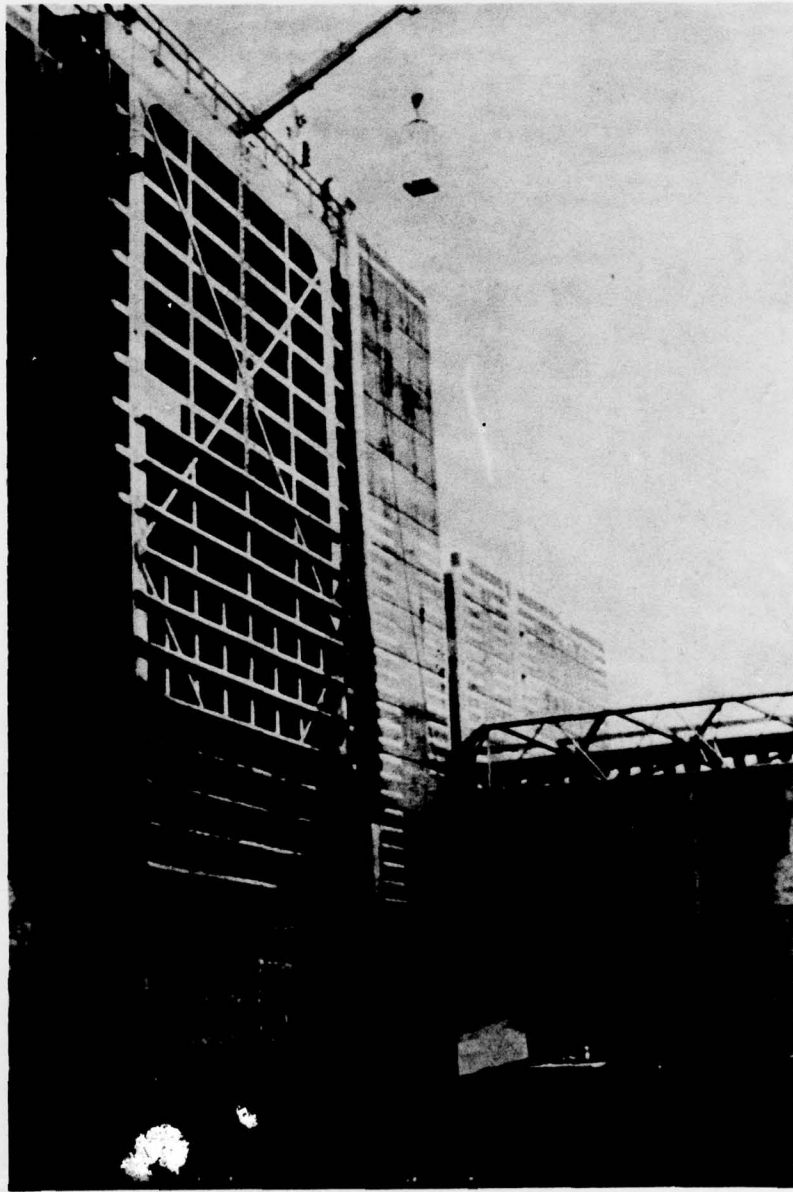
Figure 1. Dewatering of Cheatham Lock and Dam (Nashville District).
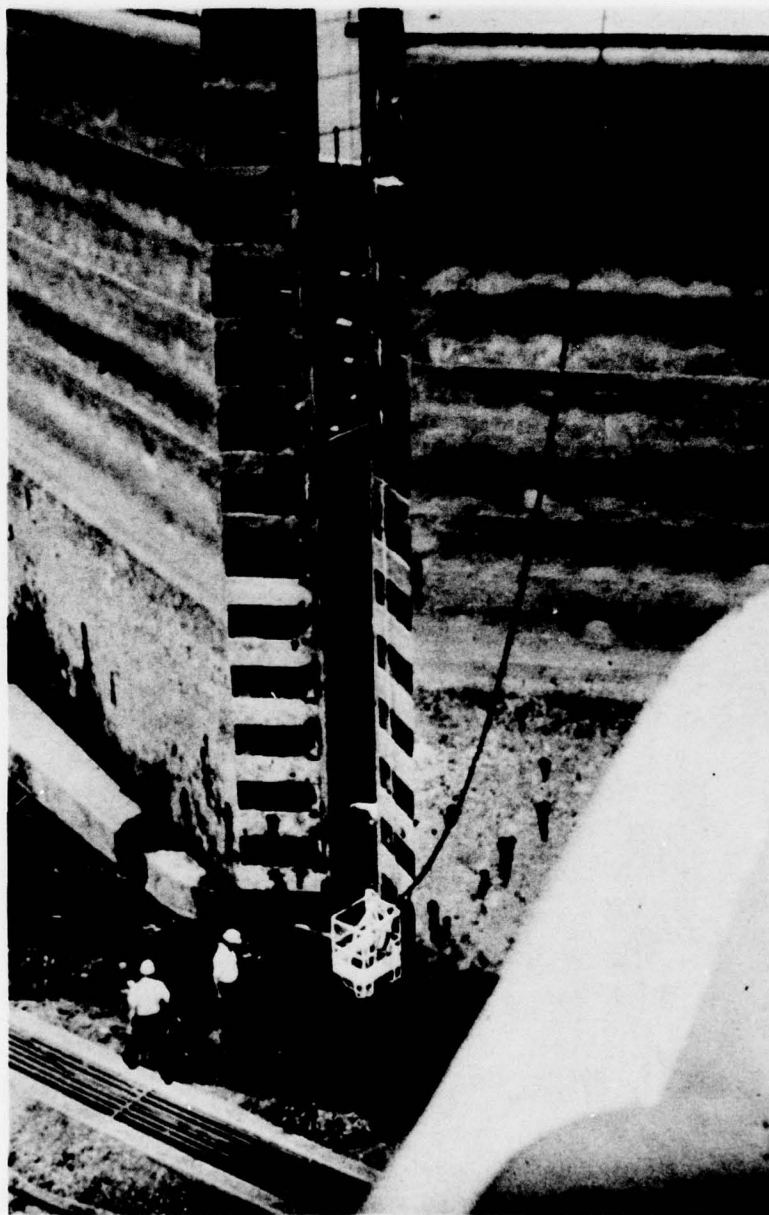
Figure 2. Miter gate showing replacement of seals at Cheatham Lock (Nashville District).

12

Figure 3. Inspection of pintel for miter gate at Cheatham Lock (Nashville District).

Table 1
Characteristics of Anodes

Galvanic Anodes

Metal	A-hour/lb (actual)*	Efficiency	Corrosion Potential [V(Cu/CuSO$_4$)]	Price Factor
Aluminum	1250	95	−1.2	1.50
Zinc	355	95	−1.1	1.00
Magnesium	500	50	−1.6	2.00

Impressed-current Anodes

Material	Max Working Capacity/sq ft Amperes		Approx Wastage lb/A-year
	Soil	Water	
Scrap steel	0-5	0-5	15-20
Scrap cast iron	0-5	0-5	10-15
Silicon iron	3	3-4	1-2
Graphite	1	2	2
Lead	—	10-20	—
Lead/platinum	—	1000	—
Platinum	—	<1000	—
Platinized titanium	—	<1000	—
Platinized niobium	—	<1000	—
Aluminum	—	2	9

*Metric conversion: 1 A-hour/lb = 2.2 A-hour/kg; 1 lb/A-year = 2.2 kg/A-year; 1 in. = 25.4 mm; 1 lb = 0.453 kg; 1 sq ft = 0.09 m^2.

Table 1 (cont'd)
Characteristics of Anodes

Composition of High Silicon Chromium Bearing Cast Iron (HSCBCI)

Element	Percent Composition
Silicon	14.35 (min)
Chromium	4.50
Carbon	0.95
Manganese	0.75
Iron	Remainder

Standard HSCBCI Anodes

Type	Nominal Size (in.)	Weight (lb)	Area (sq ft)	General Application	Special Features
B	1 × 60	12	1.4	Freshwater tanks	Each end enlarged to 1-1/2-in. diameter with cored opening for joining
C	1-1/2 × 60	25	2.0	Open box coolers requiring lengths greater than 5 ft	Uniform 1-1/2-in. diameter with cored opening both ends for joining
CD	1-1/2 × 60	26	2.0	Ground bed with backfill	One end only enlarged to 2-in. diameter with cored opening for cable connection
CDD	1-1/2 × 60	26	2.0	Ground bed with backfill permits joining in series	Each end enlarged to 2-in. diameter with cored opening for cable connection
D	2 × 60	44	2.6	Ground bed without backfill	Uniform 2-in. diameter with cable connections on one end only
M	2 × 60	60	2.8	Mild saline or deep well without backfill	Each end enlarged to 3-in. diameter with cored opening for joining
J	3 × 36	80	2.5	Severe ground, deep-well, or seawater without backfill	One end only enlarged to 5-in. diameter with cored opening for cable connection
E	3 × 60	110	4.0	Severe ground, deep-well, or seawater without backfill	One end only enlarged to 4-in. diameter with cored opening for cable connection
SM	4-1/2 × 60	220	5.5	Seawater with current discharge per anode	Uniform 4-1/2-in. diameter with cored opening each end (permits two cable connections, if required)

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*Metric conversion: 1 A-hour/lb = 2.2 A-hour/kg; 1 lb/A-year = 2.2 kg/A-year; 1 in. = 25.4 mm; 1 lb = 0.453 kg; 1 sq ft = 0.09 m².

Table 1 (cont'd)
Characteristics of Anodes

Special HSCBCl Anodes

Type	Nominal Size (in.)	Weight (lb)	Area (sq ft)	General Application	Special Features
FW	1-1/8 × 9	1	0.2	Elevated freshwater tank	Lightweight flexible assembly with continuous cable
UJx FC	1-1/2 × 9	4	0.3	Dist system in ground trench	Cored opening each end for joining anodes in series
B	2 × 9	5	0.4	Underground cables in ducts	Inside configuration permits single center cable-to-anode connection
B-30	1 × 30	7	0.7	Telephone or electrical ground rod	Cable connection end 1-1/2-in. diameter (half of Type B anode)
C-30	1-1/2 × 30	12-1/2	1.0	Dist system for more difficult applications	Cable connection end 1-1/2-in. diameter (half of Type C anode)
CD-30	1-1/2 × 30	13	1.0	Dist system for more difficult applications.	Cable connection end 2-in. diameter (half of Type CDD anode)
M-30	2 × 30	30	1.3	Dist system for more difficult applications	Cable connection end 3-in. diameter (half of Type M anode)
K-3	3 × 3	6	0.25	Small heat exchangers and like structures with limited mounting area	Button anode with integral cast bolt for attaching to structure using suitable gasket
K-6**	6 × 2-1/2	16	0.5	Ship hull lock gate, heat exchangers or other structure with large, flat surface	Button anode with integral cast bolt for attaching to structure using suitable gasket
K-12	12 × 3-7/16	53	1.0	Ship hull, heat exchangers or any other structure with large, flat surface	Button anode with integral cast bolt for attaching to structure using suitable gasket

*Metric conversion: 1 A-hour/lb = 2.2 A-hour/kg; 1 lb/A-year = 2.2 kg/A-year; 1 in. = 25.4 mm; 1 lb = 0.453 kg; 1 sq ft = 0.09 m^2.

**Note that button anode (Type K-6) is recommended for cathodic protection of lock gates.

The North Pacific Division (NPD) has successfully used sacrificial cathodic protection to prolong the life of coatings on intake gate structures (Figure 4). NPD found that some of the pipes which carried hydraulic oil to the intake gates for turbines (Figure 5) were developing corrosion pits and holes within 5 years. NPD installed sacrificial magnesium anodes in an attempt to increase the life of the coating; after 15 years of service, only the magnesium anodes had to be replaced (Figure 6) at the Dalles and John Day Powerhouse.

15

Figure 4. Cathodic protection by sacrificial magnesium anodes of intake gates in Portland District (Dalles Lock and Dam).
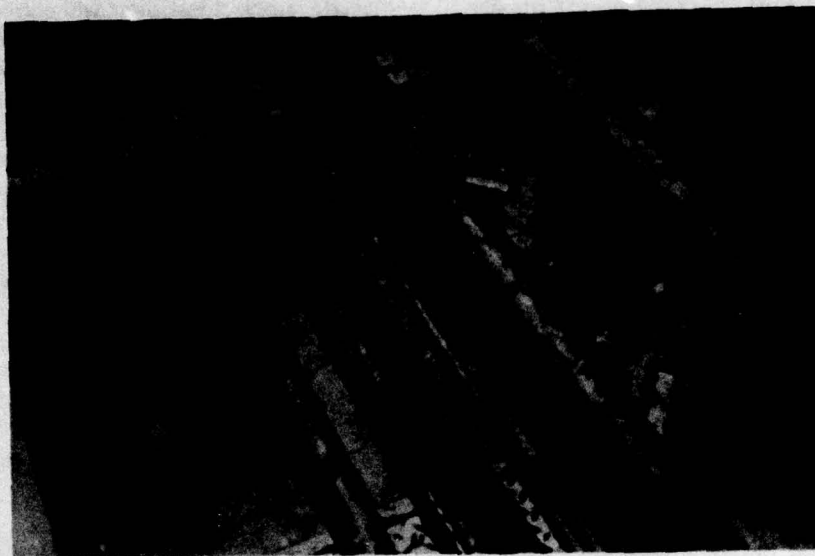
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Figure 5. Pipes from Portland District with magnesium anodes.
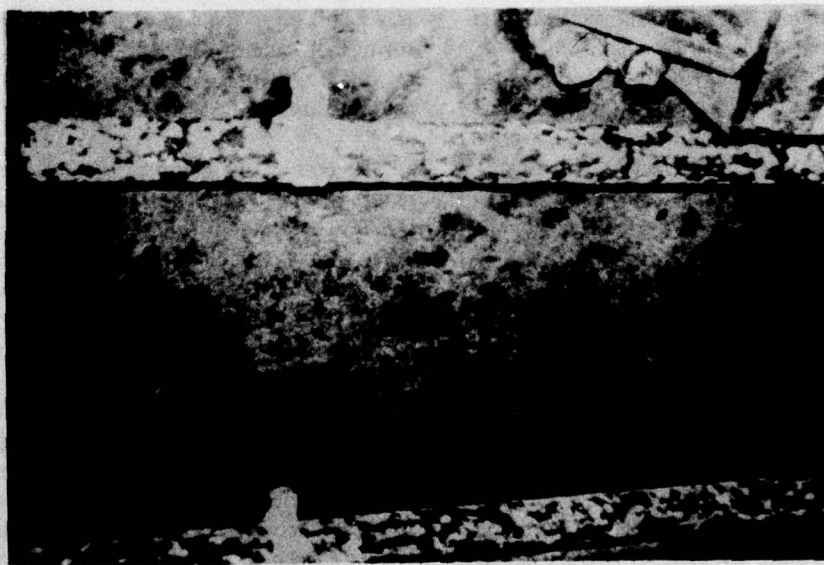

Figure 6. Used magnesium anodes after 15 years of exposure.

Cathodic protection by sacrificial magnesium anodes eliminated the pitting problem on oil lines. Cathodic protection also made repainting of the gate (which had many recesses) unnecessary and reduced the pitting on the gates' stainless steel rollers (Figure 7). An impressed-current cathodic protection system for such a structure was not feasible because of shielding effects and the danger of hydrogen embrittlement of the stainless steel rollers. Detailed steps involved in the sacrificial cathodic protection design used by NPD are described in Appendix A.

The sacrificial cathodic protection of tide gates near Savannah, GA, is shown in Figure 8. A magnesium anode is shown in Figure 9. Magnesium anodes were installed every 4 to 6 ft (1.2 to 1.8 m) to provide complete coverage. Because the water had resistivity higher than 3000 ohm-cm, magnesium anodes were chosen. Zinc anodes would not have had enough "throw distance."

In impressed-current cathodic protection systems, graphite and High Silicon Chromium Bearing Cast Iron (HSCBCI) anodes can be used. In the manufacture of graphite anodes, a binder material is used to reduce porosity. It has been found that in aerated waters, the binder is attacked by the oxygen liberated at the anode, and over a period of time, the anode becomes porous. For example, graphite slab anodes such as those shown in Figure 10 have been used extensively on the Ohio River and Alabama River lock miter gates. Some anodes near the water surface at these installations have been found to be so porous and soft that divers could put their fingers into them. Therefore, the use of graphite slab anodes is not recommended since these anodes have no advantage over HSCBCI button anodes. However, rod-type anodes of graphite in protected split pipes have been successfully used by the New Orleans District at Port Allen and Algiers locks. Rod-type graphite anodes are apparently not attacked by oxygen as much as slab type anodes. The difference could be attributed to different manufacturing process for graphite rod and graphite slab anodes.

HSCBCI anodes can be procured in many sizes and shapes. One shape which has been developed for the CE is a button anode, shown in Figure 11. The electrical connection in this 6-in. (152-mm) diameter anode is provided through the body of the anode, and the anchoring bolt is electrically isolated from the body of the anode during installation. This particular design was developed after discovering that if the anchoring bolt is electrically connected to the body of the anode, an electrical short will corrode the button anode bolt rapidly, and the anodes will fall off. This actually happened at the Freshwater Bayou Lock in the New Orleans District where 12-in. (304-mm) diameter, ship-type button anodes were used (Figure 12). Six-inch (152-mm) diameter button anodes have been used by the Mobile District on the Alabama and Black Warrior Rivers for the past 7 years and have performed very well (Figure 13). Defaulted button anodes on miter gates can be replaced by two divers without dewatering the lock. However, at some of these lock gates HSCBCI sausage anodes (Figure 14) were used on the compartment side. Since there was no mechanical protection provided to the anodes, river debris had damaged the cables and anodes (Figure 15) and made the cathodic protection system inoperable until repaired.

HSCBCI button anodes have performed extremely well on the skin side of miter gates. A grid of button anodes every 10 to 15 ft (3 to 5 m) provides adequate protection. However, on the chamber side of a miter gate, individual button anodes are required in each compartment to prevent electrical shielding and to provide complete coverage. These compartments are enclosed on three sides and are open on one side. Since the compartments are coated, cathodic protection current will "spill over" and protect the structural parts on the open side. A new all-button cathodic protection system has been used successfully at Uniontown Lock miter gate (Louisville District). The cost of this system was 7 percent of the cost of the new miter gate. Uniontown lock miter gate leaves have used 656 button anodes. The detailed design for this system is described in Appendix B.

The cost of the cathodic protection system can be reduced somewhat by using sausage anodes made from HSCBCI or graphite on the compartment side of a miter gate. Plastic-lined steel split pipes must be used to protect these anodes from mechanical damage caused by ice and debris. However, some debris carried by the rivers, such as logs, is big (6 ft [2m] long × 2 ft [0.6 m] in diameter) and has damaged cables, pipes, and anodes such as that observed on the Ohio River locks (Figure 16). A satisfactory solution to this problem has not yet been found. A tough and durable anode material which can be mounted and protected from the debris is needed. Platinized anodes (Figure 17) have been used by the offshore industry and are being investigated for applications in CE structures.

18
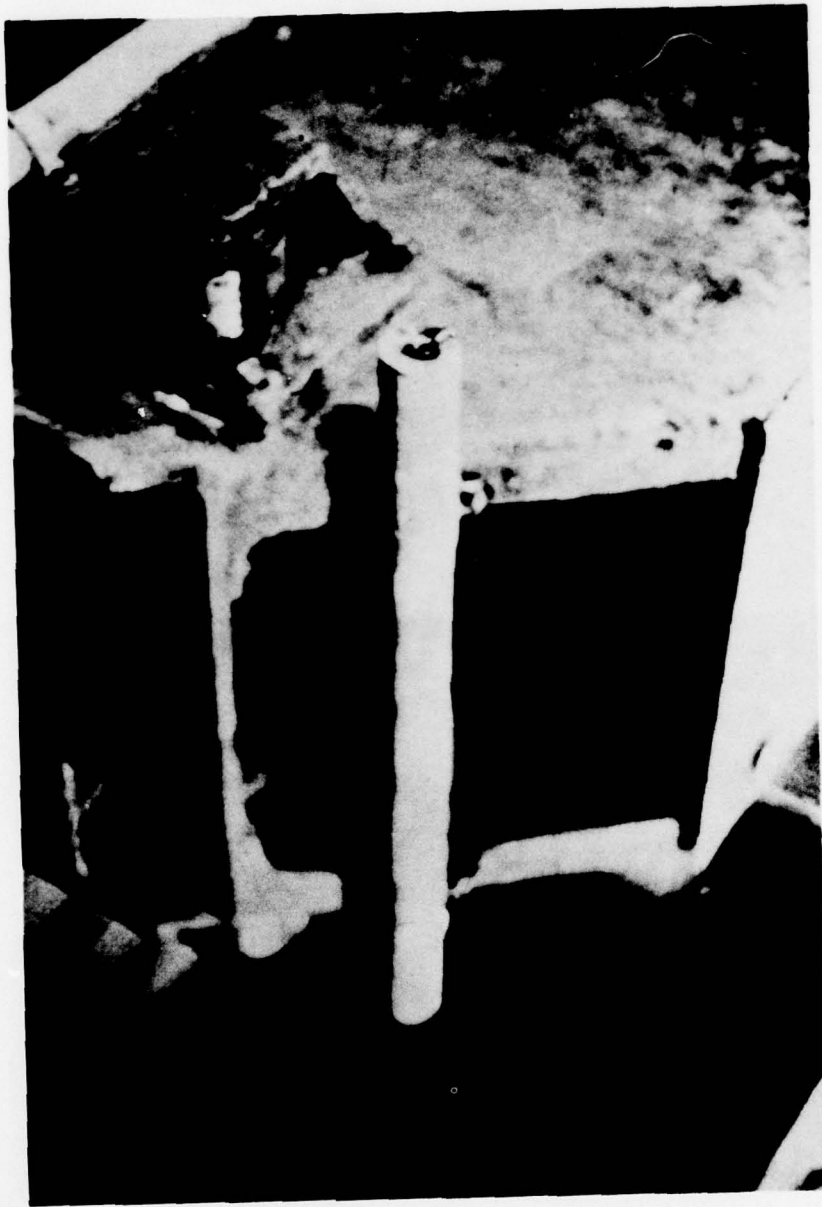
Figure 7. Intake gate with magnesium anodes.

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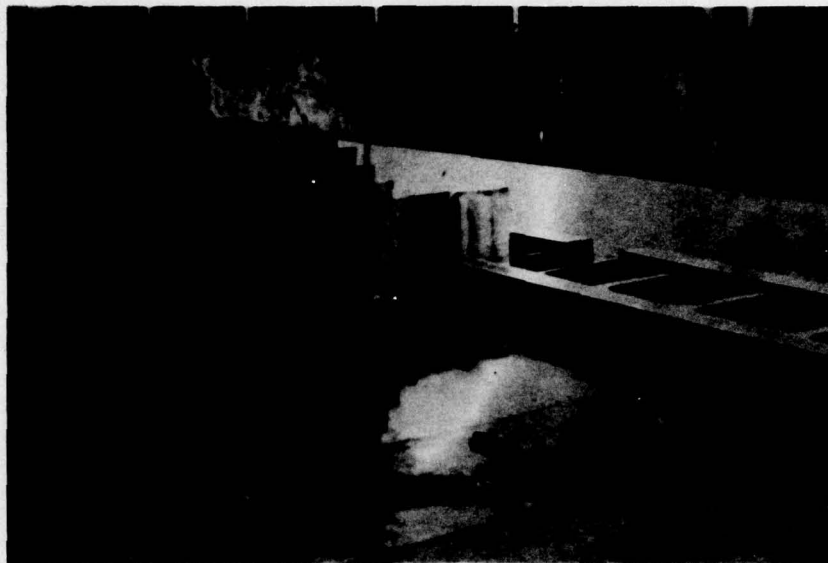
Figure 8. Savannah tide gate with magnesium anodes.
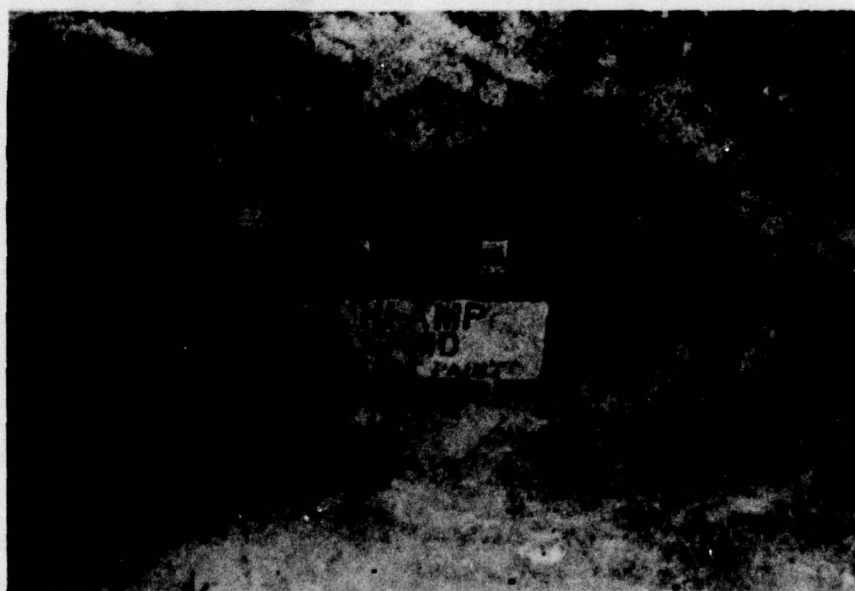
Figure 9. Magnesium anodes on the tide gates.

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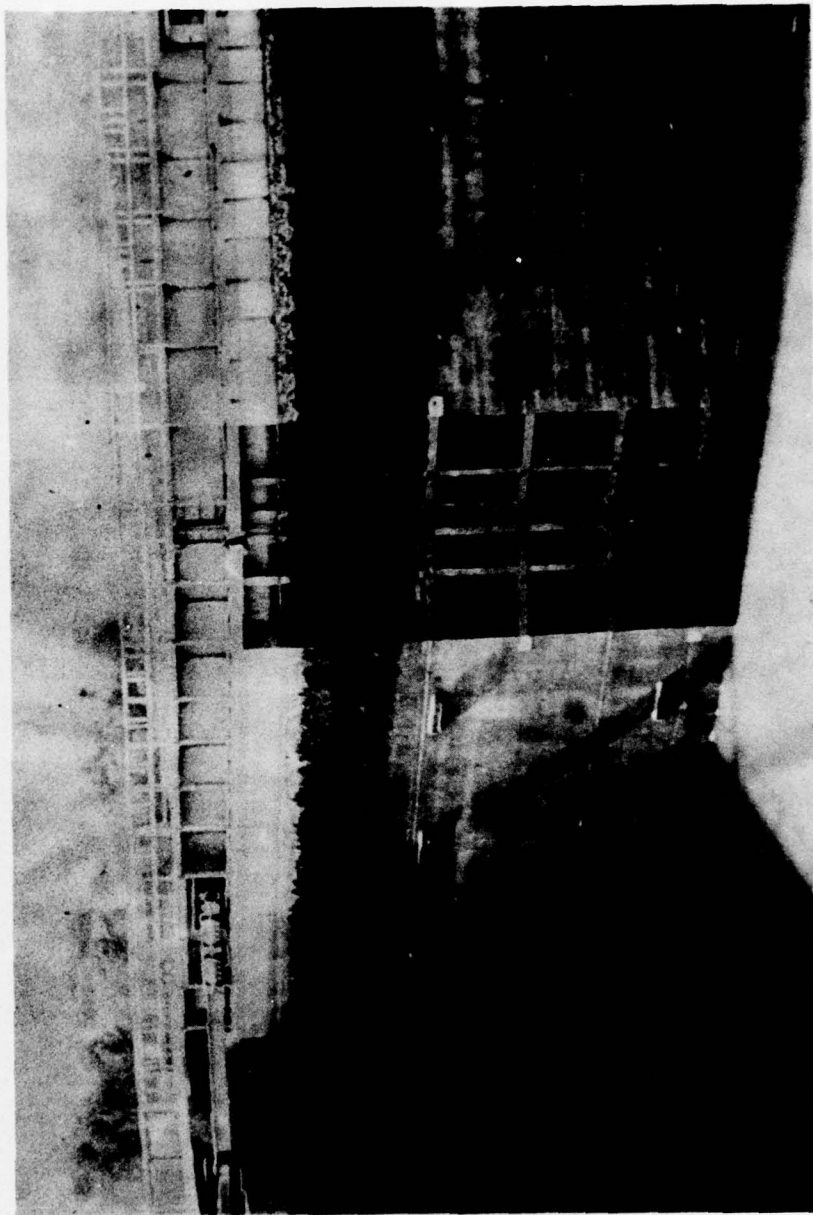
Figure 10. Mobile District Lock gate using slab anodes.

Figure 11. Type K-6 button anode design showing electrical connection such as that used at Mills Ferry miter gate (Mobile District).

Figure 12. Button anode recovered from freshwater bayou (New Orleans District).
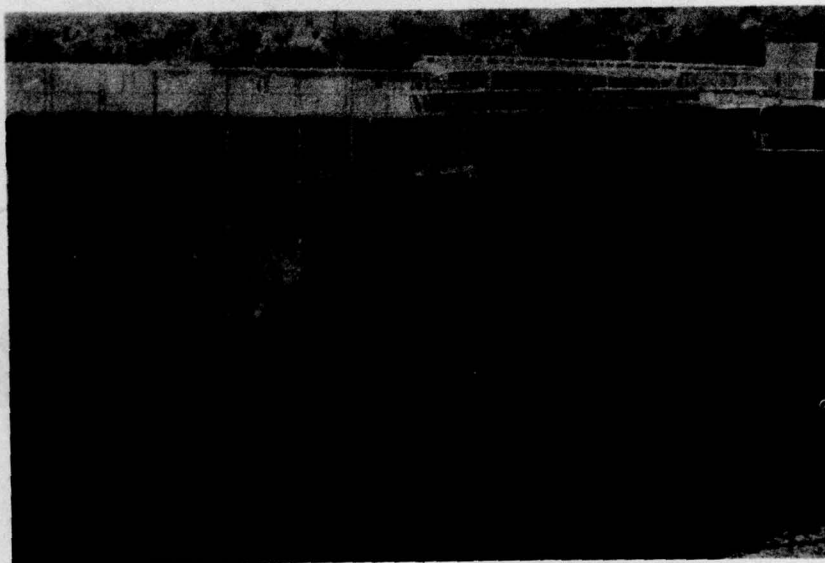
Figure 13. Mills Ferry Lock miter gate in Mobile District with cathodic protection
system. The impressed-current system used button anodes on the skin side.
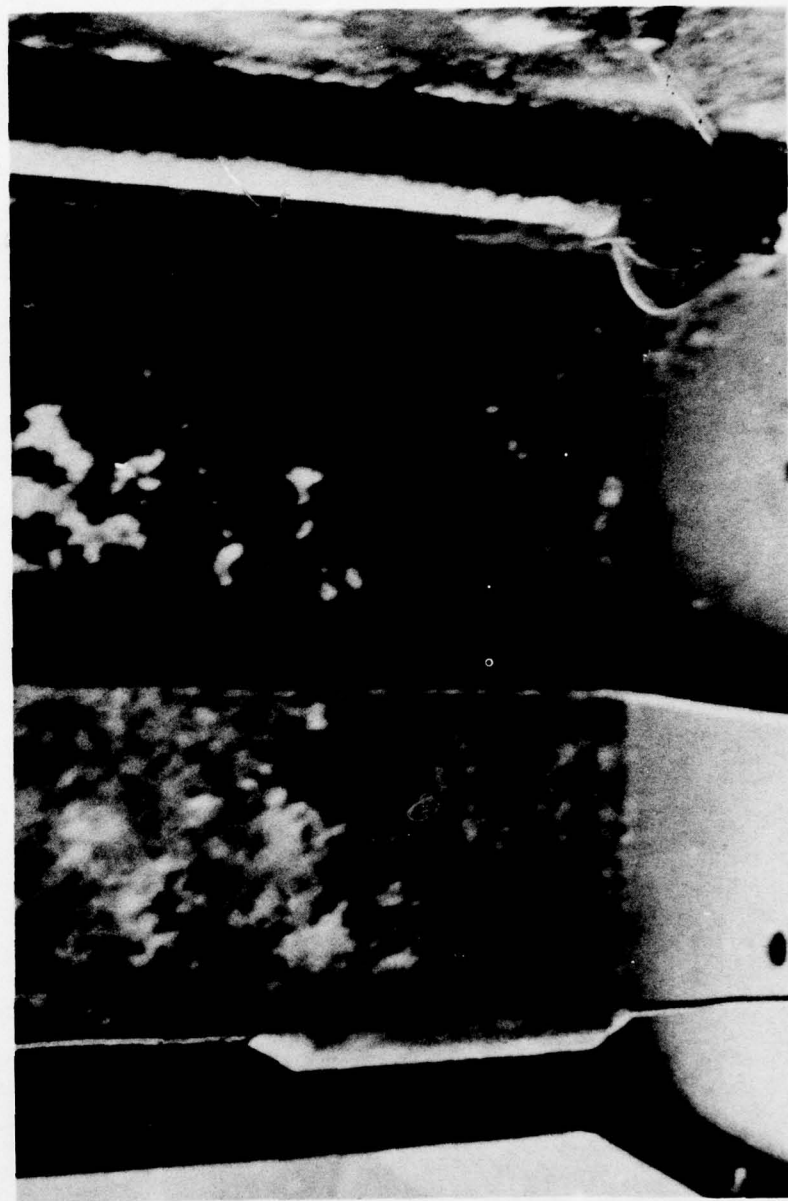
Figure 14. Sausage anode at Mills Ferry miter gate (Mobile District). The impressed-current system used sausage anodes on the chamber side.
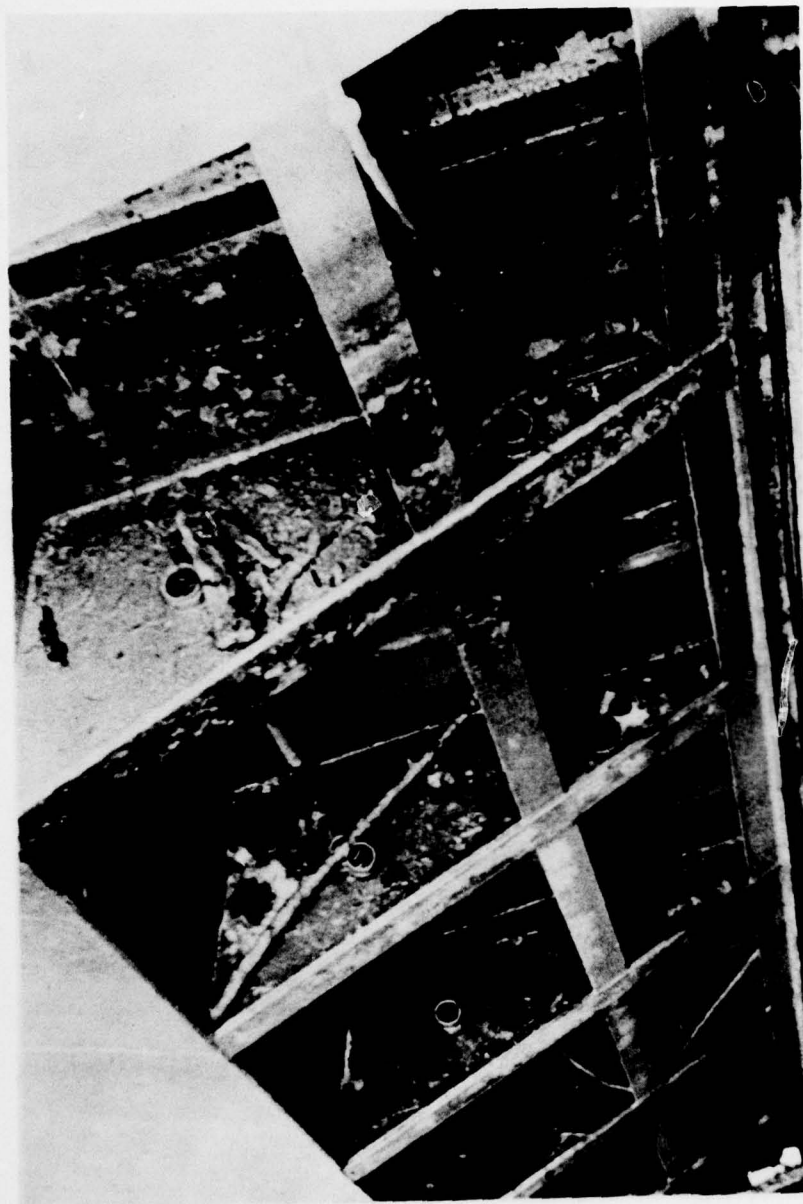
Figure 15. Damage caused by debris at Mills Ferry Lock and Dam (Mobile District). The impressed-current system used unprotected sausage HSCBCI anodes.

25
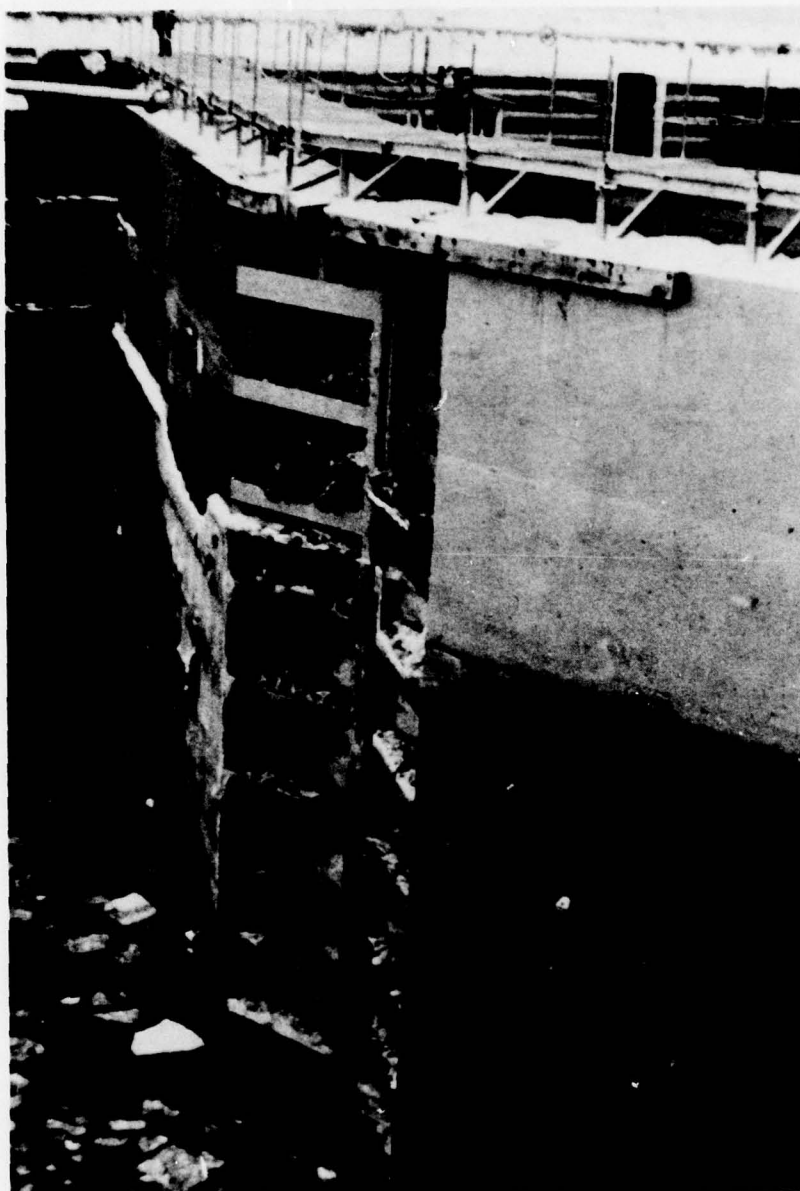
Figure 16. Ice and debris at Meldahl Lock (Louisville District).
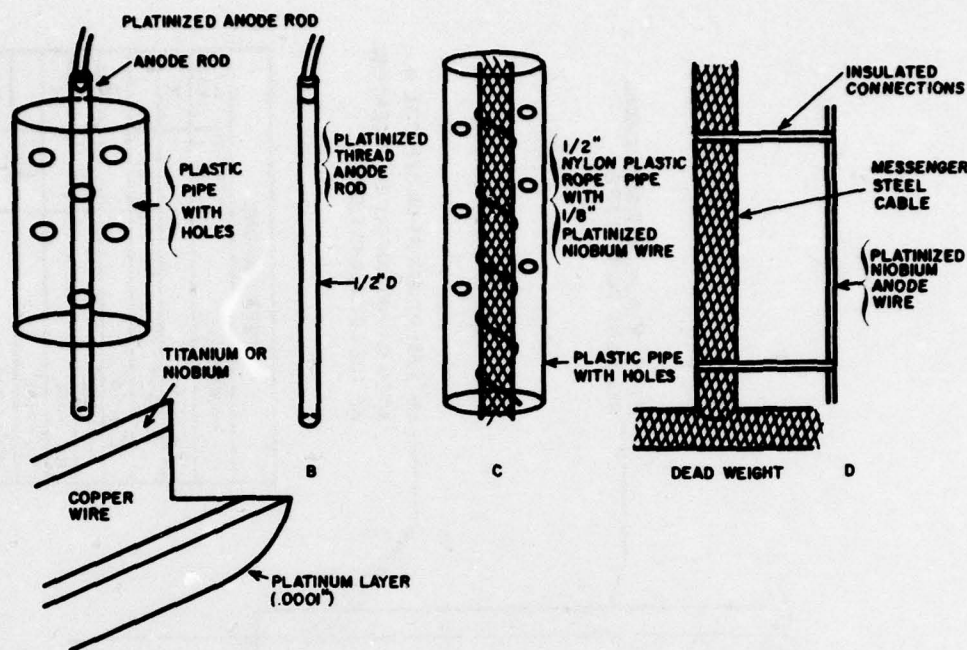
Figure 17. Platinized anodes: experimental field installation.

Four such designs which provide mechanical protection are being considered, and other configurations must also be investigated. CERL is monitoring the performance of platinized niobium and platinized titanium in side-by-side applications at the Mills Ferry Lock in Mobile District. Previously at this lock, sausage HSCBCI anodes were used without any mechanical protection. However, the previous cables and anodes had been damaged by debris and needed to be retrofit. The experimental system being installed is composed of platinized niobium and titanium wire which is 1/8 in. (3 mm) in diameter. This wire is wound on a 1/2-in. (12-mm) diameter, plastic pipe mandril (Figure 18). The anode is then placed in an outer 4-in. (101-mm) diameter, schedule 80 plastic casing which has holes cut into it. CERL experiments have shown that 90 percent of the anode output can be obtained even if 30 percent of the area of the outer plastic casing is removed (Figure 19). The outer casing does not stop the flow of current from the anode but continues to provide mechanical protection to the anodes.

Other possible systems include a platinized channel (Figure 20) mounted on the side of the compartment, or a platinized mesh or rod in a fiberglass holder, also mounted on the side of the compartment and protected from debris. Platinized anodes have great potential for applications in the cathodic protection of the chamber side of a miter gate. Platinized titanium and niobium anodes are mechanically tough and can be formed in many shapes. It is generally necessary to use only a small anode. Standard platinum thickness is 100 μin. (0.025 mm). The consumption of platinized anode is 6 mg of platinum/A/year. Current densities of the order of 200 A/sq ft (2152 A/m^2) of the anode surface can be used. To reduce the resistance of the anode, copper-cored platinized titanium and niobium are commercially available (also see Chapter 4).

Stainless steel anodes were used on the Upper Mississippi River in some experimental installations in the 1950s. Stainless steel develops a passive coating and is prone to pitting; therefore, it should not be used in cathodic protection systems as an anode material.

Coating Selection

Protective coatings are a major means of controlling the effects of corrosion. The selection of a proper coating depends a great deal on the exposures to which it will be subjected. The properties a coating must possess

27

2 1/2" 19' SCHEDULE 80 CHEMICAL RESISTANT PLASTIC PIPE

1/4"∅ PERFORATIONS ON OPPOSITE 4 SIDES OF PIPE SPACED ON 1" CENTERS. AT THE LOCATIONS LISTED.

PERFORATIONS		
LOCATIONS	PERFOR-ATED	NOT PERF.
FIRST 6"		X
6" — 42"	X	
42" — 54"		X
54" — 102"	X	
102" — 114"		X
114" — 162"	X	
162" — 174"		X
174" — 198"	X	

¢

1" TYP.

6"

BOTTOM

#8 AWG 7 STRAND "DURALAR" HALAR INSULATED LEAD WIRE CONNECTED TO ANODE WIRE AT BOTH TOP AND BOTTOM OF PLASTIC PIPE.

1/2"∅ SCHEDULE 80 CHEMICAL RESISTANT PLASTIC PIPE.

.062 PLATINIZED NIOBIUM WIRE

EXPOXY ENCAPSULATED CONNECTION OF LEAD WIRE TO Pt/Nb ANODE WIRE.

2"

4" MIN.

Figure 18. Platinized niobium anode with holder pipe.

28

Figure 19. Current and voltage as a function of percent removed area of plastic pipe.

PLATINIZED REGION

TITANIUM OR NIOBIUM SUBSTRATE

15°

RECESSED MOUNTING

Figure 20. Platinized channel configuration which can be considered for field installations.

to withstand atmospheric exposures will differ from those required to withstand water immersion. Factors such as water corrosivity (resistivity, pH, chloride content, oxygen concentration, and hardness); turbulent and/or abrasive flow; type of substrate; and materials and labor costs all influence coating selection.

In general, vinyl coatings perform well in quiet freshwater; they usually have a lifetime of 20 or more years. However, vinyl coating life is considerably decreased by damage caused by debris and turbulent water. In brackish water (resistivity less than 2500 ohm-cm), the performance of vinyl coatings becomes marginal and the use of epoxies for added chemical resistance is necessary.

Seawater, which contains approximately 3.5 percent salt and a fair amount of organic biomass, is a severe exposure area. Even the best coatings (e.g., coal tar epoxy) may only last 5 to 10 years in seawater. The splash zone is a particular problem area. However, zinc-rich coatings, which eliminate or reduce rust undercutting, can be of some value in the splash zone area.

The immersion and maintenance coatings most commonly used by Civil Works are shown in Table 2. Although some of the general criteria for coating selection have been mentioned above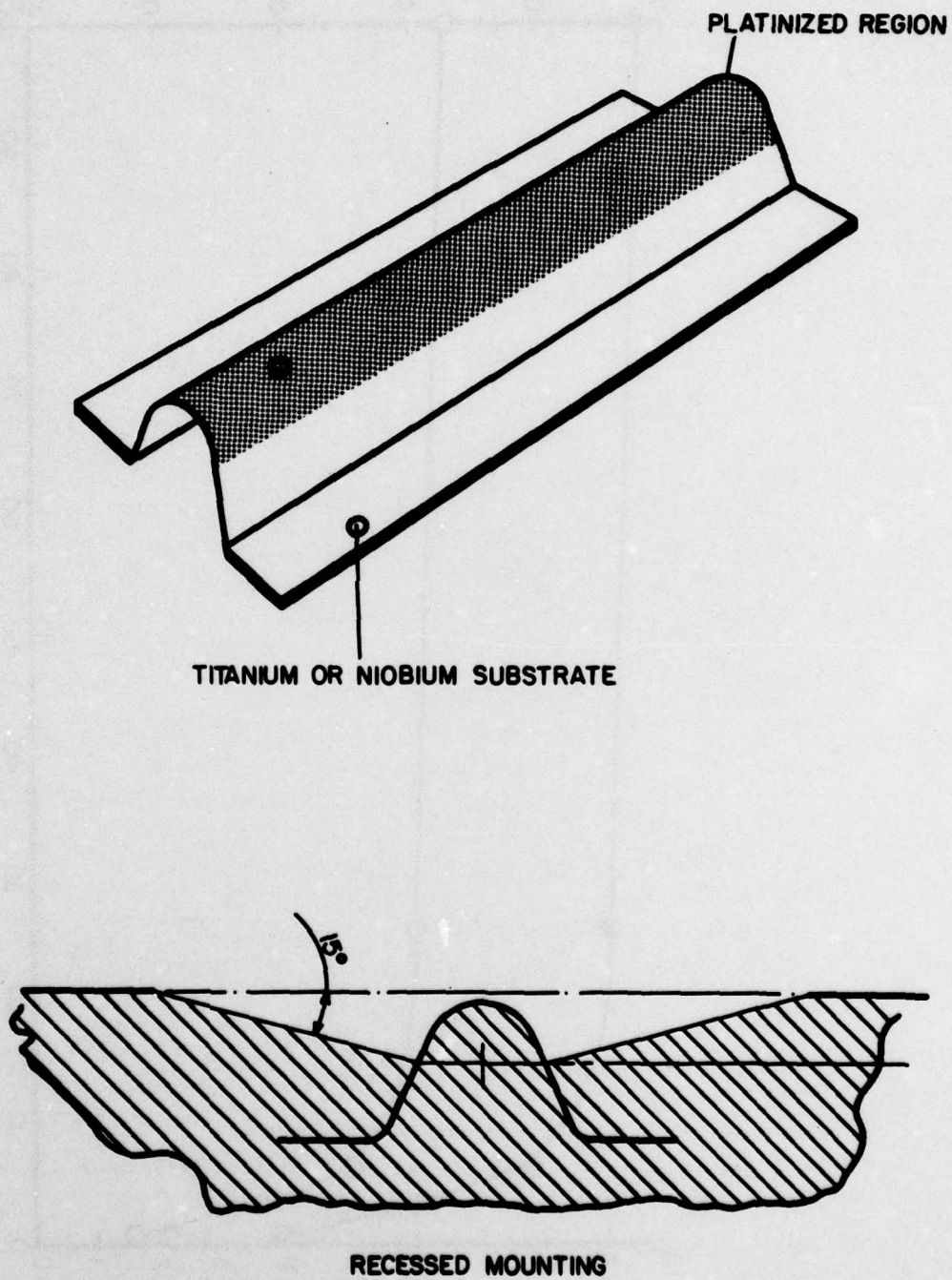, a complete guide to coating selection is beyond the scope of this report. Engineer Manual (EM) 1110-2-3400 and Civil Works Guide Specification CW-09940 provide a detailed selection guide.[5]

Although coatings are a major form of corrosion control, no coating is perfect. All coatings have at least some porosity to water and chloride ions, in many cases through pinholes and other mechanical defects in the film. Considering these defects and certain types of severe exposures, the use of cathodic protection in conjunction with the coating system may be warranted. Cathodic protection must be considered for areas which are mostly or completely inaccessible for painting even in medium to high resistivity water (4000 to 10,000 ohm-cm). Cathodic protection can even be an

economic alternative to coatings for mitigating corrosion of submerged seawater structures.[6]

Coating Condition

Investigations have revealed that cathodic protection increases the life of the coating by preventing undercutting at damaged areas. In the design of cathodic protection systems, the engineer must know or predict what the condition of the coating is likely to be in the next 15 to 20 years of service. Current distribution in cathodic protection is greatly improved by even a relatively poor coating; and *during* cathodic protection, polarization is accompanied by the deposition of a carbonate coating (which is sometimes as good as the paint coating), thereby further protecting the steel. Carbonate scale also helps the even distribution of the cathodic protection current.

A bare plate of steel in freshwater requires approximately 2 mA/sq ft (22 mA/m^2) for cathodic protection in quiet water.[7] If the velocity of the water is increased to 4 ft/s (1 m/s), then the current required increases as a square root of the velocity, to 20 mA/sq ft (215 mA/m^2). A painted steel surface requires only about 0.2 mA/sq ft (2.2 mA/m^2) for cathodic protection in moving water. In hydraulic structures such as miter gates, the cathodic protection current in an operational cathodic protection system in Mississippi River water (resistivity 3200 ohm-cm) has been estimated to be 2 mA/sq ft (22 mA/m^2) of the painted surface. It is obvious that most of the current requirement for a painted structure is attributed to straying, which is defined as the current finding its way through alternate paths and not through bare areas in the painted miter gate.

Current Distribution

All coatings degrade with age, and it is generally assumed for design considerations that 10 to 30 percent

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[5]*Paint Manual—New Construction and Maintenance*, Engineer Manual (EM) 1110-2-3400 (Department of the Army, 31 May 1967), pp 114-156; and *Painting: Hydraulic Structures and Appurtenant Works*, Guide Specification CW-09940 (Department of the Army, January 1977), pp 70-127.

[6]H. H. Uhlig, *Corrosion and Corrosion Control* (John Wiley and Sons, Inc., 1963); M. G. Fontana and N. P. Greene, *Corrosion Engineering* (McGraw-Hill Book Co., 1967); *Recommended Practice for Control of External Corrosion*, RP-01-69 (NACE, 1969); L. M. Applegate, *Cathodic Protection* (McGraw-Hill Book Co., 1960); and J. L. Rhowedder and F. W. Shanks, *Cathodic Protection Investigation*, CWI No. 311 (U.S. Army Corps of Engineers Rock Island District, March 1954).

[7]*Electrical Design: Corrosion Control*, TM 5-811-4 (Department of the Army, 1 August 1962).

Table 2
Immersion and Maintenance Coatings

IMMERSION COATINGS

Epoxy Paints

Paint Specification	Pigment	Remarks
E-303	Zinc dust	3-component primer
C-200	Coal tar	2-component (can be self-priming, heavy bodied, performs well over E-303)
MIL-P-24441	Various colors	Numerous formulations (performs well over E-303)

Vinyl Paints

Paint Specification	Pigment	Remarks
VZ-108	Zinc dust	3-component primer
V-766	White or gray TiO_2	(self-priming, outstanding adhesion)
V-106	Red iron oxide	Self-priming, harder than V-766
V-102	Aluminum	Topcoat over V-766 or V-106
V-103	Carbon black	Topcoat over V-766 or V-106

Wash Primer System (Vinyl)*

Paint Specification	Pigment	Remarks
MIL-P-15328	Zinc chromate	Wash primer 0.3–0.5 mil thick
MIL-P-15929	Red lead	Intermediate coat over wash primer

MAINTENANCE COATINGS

Primer Paints

Paint Specification	Pigment	Binder	Remarks
TT-P-86 Type I	Red lead	Linseed Oil	Penetrates, dries slowly
TT-P-86 Type II	Red lead + Fe_2O_3	Oil Alkyd	Some penetration, faster dry
TT-P-86 Type III	Red lead	Alkyd	No penetration, good weathering
TT-P-86 Type IV	Red lead	Phenolic	No penetration, withstands immersion
TT-P-615 (various types)	Basic lead silico chromate	Various Linseed Oil Alkyd Combinations	Similar to TT-P-86 except no straight linseed oil and no phenolic

Top Coat Paintings

Paint Specification	Pigment	Binder	Remarks
TT-P-38	Aluminum	Phenolic	Excellent weathering, withstands immersion
TT-E-489 gloss	Light stable colors	Alkyd	Less expensive than silicone alkyds
TT-E-490 semigloss		Silicone Alkyd	Retains color and gloss better than 489
TT-E-1593 gloss		Silicone Alkyd	

*May use any of numerous vinyl topcoat paints.

of the miter gate will be bare after 20 years.[8] In actual practice, the amount of current straying from the miter gate far exceeds the current requirements for polarization of the intended surface. Most of the cathodic protection current requirement is attributed to straying, which is also a function of gate size or surface area. Therefore, for design considerations, the figure used in cathodic protection systems is 2 mA/sq ft (22 mA/m^2) of coated surface area of the miter gate. This figure is used even though a painted surface requires only 0.2 mA/sq ft (2.2 mA/m^2) to maintain polarization in freshwater.

The current required for cathodic protection increases with the bare surface area and water velocity. The effects of water velocity are extremely important in the current requirements for the downstream side of the tainter gates. For example, because of the high velocity water and abrasion at some tainter gates in the Ohio River Division, even the best coatings on the downstream side do not last more than 2 years, causing splash zones at the downstream sides of the tainter gates to rust to the extent that they require continual repainting. However, a row of button anodes mounted 2 ft (0.6 m) below the water surface could protect this steel surface from corrosion—if the anodes are protected from debris, they could last 20 years.

In cathodic protection design, a good current distribution should be used to avoid shielding, straying, and interference. Current from an anode has to travel to the protected surface. If the anode cannot "see" the surface, the surface does not receive cathodic protection current. Scratches in painted surfaces act like sinks and distort the electric field distribution. The path of the cathodic protection current can be traced by electric field plot. Experiments have shown that a bare plate of steel can completely distort the current distribution path, as shown in Figure 21.[9] It is shown in Figure 21 that there is little cathodic protection current on the backside of the bare steel plate which is facing the anode. Thus, only one side of a steel surface can be protected by one set of anodes. A second set would be required for the other face. Areas which cannot "see" the anode do not receive any current.

Although shielding must be considered in any cathodic protection system design, a good painted surface

can minimize shielding problems. However, if the paint film is scratched on a large area near the anode, then most of the current will go to the scratched area near the anode and not to areas farther away from the anode. Straying of cathodic protection current is defined as that portion of the cathodic current which does not go to the intended surface; i.e., the current finds its way back to the source without polarizing the intended structure. Flat painted surfaces do not present as much of a problem as compartments. For example, a miter gate (Figure 22) has many compartments which are enclosed on three sides and open on one side to water. At first it would seem difficult to obtain satisfactory current distribution on areas such as the lock gate which has many recesses, channels, angles, and structural members with faces turned away from the anode and therefore not in the direct path of the cathodic protection current. An experimental installation on the Upper Mississippi River showed that although current distribution was poor for several months after cathodic protection was applied, the distribution improved gradually as deposition of carbonate coating progressed. The deposition of the carbonate coating increased the electrical resistance and reduced the distortion of the current path, in addition to decreasing the corrosion rate of the steel. This experiment demonstrated that a good coating is a necessary adjunct to cathodic protection.

If the anodes are located some distance away from the structure, current will stray and the possibility of interference from other parts of the structure will increase. Since the resistivity of the concrete is approximately eight times the resistivity of the water, only a small portion of the current will go through the concrete walls of the lock chamber. However, if the lock walls are embedded with reinforcing steel, current from the anodes might go to the concrete, through the steel in the concrete, and back to the rectifier. In this case, corrosion will take place where the current leaves the embedded steel.

The by-products of steel corrosion occupy a volume fifteen times the volume of the steel, which exerts substantive tensile forces and debonds the concrete from the embedded steel. The bonding strength of the concrete is reduced by excessive straying and might even lead to concrete spalling. Therefore, a cathodic protection system design for miter gates must locate anodes *on* the hydraulic structure, *not* in the lock bottom. Experiments with anodes mounted at the bottom of the Mississippi River lock gates showed that a large amount of current was straying through the lock walls.

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[8] *Electrical Design: Corrosion Control*, TM 5-811-4 (Department of the Army, 1 August 1962).

[9] F. W. Kearney, *Corrosion Control in Civil Works: Cathodic Protection*, Interim Report M-222/ADA045184 (U.S. Army Construction Engineering Research Laboratory [CERL], July 1977).
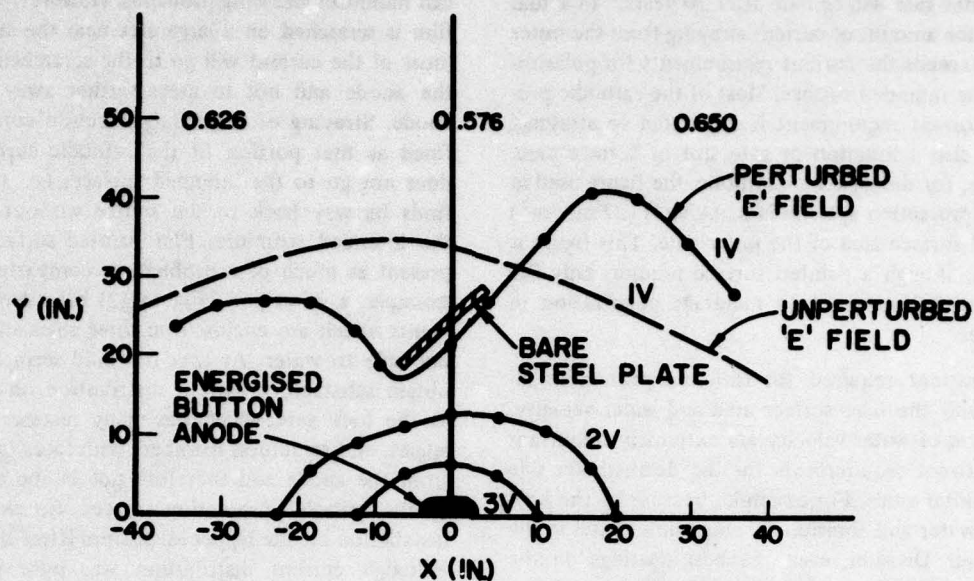
Figure 21. Distortion of electric field path caused by a bare steel plate.
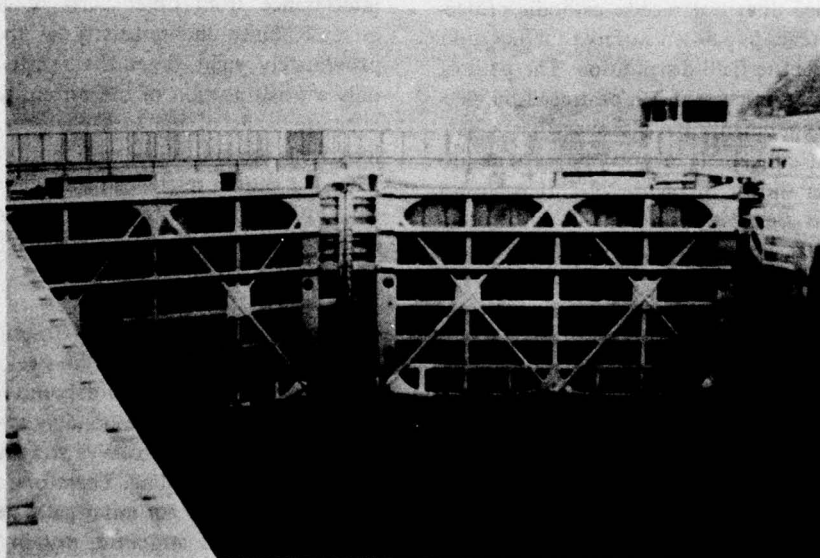

Figure 22. Cordell Hull Lock Gate with impressed-current cathodic protection, button anodes (Nashville District).

34

In an experiment on the Mississippi River, Rhowedder and Shanks determined that a long steel cable located 500 ft (152 m) upstream from roller gates forced only 5 A into the gates when 100 A were discharged from the anode into the river.[10] The remaining current (95 A) found alternate paths to the rectifier through the reinforcing steel in the lock wall and armored noses of the piers.

CERL field surveys on miter gates have shown that a single leaf of the miter gate without any visible paint-damaged area drains about 5 A of current. Most of this current is attributed to straying and goes elsewhere without polarizing and protecting the intended structure.

Resistance of the Electrical Circuit

The resistance of a cathodic protection circuit is the sum of the resistance of the anodes, resistance of the anode/electrolyte interface R, and resistance of the cables. The resistance of the cylindrical anodes surrounded by water R can be estimated by the following equation:

$$R = \frac{0.012 \; P \; Log_{10} \; \dfrac{\text{Distance between anode-cathode (ft)}}{\text{Radius of the anode (ft)}}}{\text{Length of the anode (ft)}} \qquad \text{[Eq 1]}$$

where: R is the resistance of the anode in ohms

P is the resistivity of the electrolyte surrounding the anode in ohm-cm.

Equation 1 assumes that anodes are symmetrically placed and the current flow from the anode to the cathode is radial. It shows that the resistance of the anode/electrolyte interface increases with the resistivity of the water surrounding the anode. Increasing anode length decreases the electrical resistance of the anode to water. Increasing the anode's diameter has a lesser effect on the resistance of the anode.

The resistance of button-type anodes cannot be estimated by the above equation since the current flow from the anode to structure is not radial. The resistance of type K-6 HSCBCI button anode is shown in Table 3.

Table 3
Comparative Resistances of Type K-6
(6 in. Diameter HSCBCI Button Anodes)

Configuration	Resistance (ohms)	
	Freshwater	Salt Water
One anode—small diameter	92.6	0.755
Two anodes—far apart	44.2	.608
Three anodes	27.5	.500
Two anodes—close together	56	.583
One anode—large	66.2	.739

In estimating the total resistance of the cathodic protection circuit, the cable resistance must also be considered. The resistance of the No. 2 AWG Neoprene-coated copper cables used in cathodic protection systems is proportional to the length of the cable and equals 0.159 ohm/1000 ft (0.048 ohm/m). Since splicing underwater is not recommended, individual cables from button anodes are brought through a conduit to an electrical junction box above the water level. Sometimes additional resistors have to be added at the junction box to balance the voltage at the individual anode groups since the rectifier is set at a fixed potential. Anodes near the top of the miter gate will have higher impressed voltages than the anodes near the bottom of the gate because of the IR drop in the cable.

Automatic rectifiers which have a feedback loop are available commercially. These rectifiers have a reference electrode which is permanently installed near the structure. The feedback circuit automatically regulates the voltage, maintaining a constant potential between the structure and the permanently installed reference cell. Evaluations at CERL have shown that if the reference cell is damaged by fouling or by some other means, the rectifier will continue to increase the voltage.[11] This could cause the paint to blister. An output over-voltage protection must be specified if automatic rectifiers are to be used. (Note: automatic rectifiers are still experimental and are not widely used.)

In cathodic protection systems for miter gates, locks are filled and emptied many times during the day. When the lock is full, more anodes are in the water, thereby reducing the total resistance of the cathodic protection circuit and increasing the current. When the

[10] J. L. Rhowedder and F. W. Shanks, *Cathodic Protection Investigation*, CWI No. 311 (U.S. Army Corps of Engineers Rock Island District, March 1954).

[11] F. W. Kearney, *Corrosion Control in Civil Works: Cathodic Protection*, Interim Report M-222/ADA045184 (CERL, July 1977).

lock is empty, fewer anodes are in the water and the total resistance of the cathodic protection circuit is increased, which reduces the current. This has a self-compensating effect on the resistance of the circuit. Therefore, rectifier adjustments with each emptying and filling are not necessary to compensate for the changing current requirement.

Once the carbonate film is formed on the polarized steel surface, it takes a few days to depolarize. Therefore, cathodic protection is maintained during lock emptying and filling operations. A transient rush of high velocity water does not increase the current requirement because of the presence of polarized film such as carbonate deposit on the steel surface.

Some structures, such as tainter gates, can be repainted without dewatering by dropping emergency bulkheads. Other hydraulic structures, such as submerged portions of the miter gates, cannot be repainted or retouched without dewatering. Cathodic protection provides supplemental protection to such submerged areas. The condition of the coating and the water resistivity determine the anode spacing. In freshwater, even for newly painted surfaces, impressed-current anode spacing should not be more than 15 ft (5 m). This is because the IR drop in freshwater reduces the throw distance of the anodes. If the anodes are spaced farther, higher voltages are required to achieve complete cathodic protection. Applied voltages more than 5 V (rectifier voltage) at the anodes may cause the paint to blister near the anode. As shown in Figure 23, paint blistering is caused by the pressure of hydrogen which is evolved at the steel surface. The threshold voltage for paint blistering depends on the type of coating and thickness of the coating. Thicker coating can withstand higher voltages. Areas near the sharp edges of structural members, rivet heads, and welds are not likely to have adequate paint thickness, and therefore are more prone to blistering. To avoid blistering in water storage tanks, the National Association of Corrosion Engineers (NACE) recommends that steel surfaces should not be polarized to a voltage more negative than -1.20 V with respect to the copper-copper sulphate reference electrode. Experiments at CERL have shown that steel surfaces properly coated with a 6-mil-thick vinyl paint can withstand surges of 10 V of circuit voltage. However, if a defect is present in the paint film, blistering will start immediately, and the cathodic protection voltage will accelerate the blistering process. It is recommended that no more than 5 V of rectifier output voltage be impressed on the anode. The half cell voltage of the polarized structure should not be more than -1.2 V with respect to copper-copper sulphate.

Structural Configuration

The configuration of the hydraulic structures (i.e., miter gates, intake gates, tainter gates, tainter valves, or mooring bits) determines the anode location.

Miter gates have a skin plate on one side and compartments which are open to water on the other side. Button anodes are durable and do not need additional mechanical protection. Mounting button anodes on the skin plate is a rather simple operation. Button anodes are electrically isolated from the gate structure, since the electrical connection is made through the body of the anode (Figure 11). The anchor bolt is electrically isolated from the body of the button anode. (A detailed design of button anodes for Uniontown Lock is described in Appendix B.) If sausage anodes are used on the skin side, timber guards must be provided to protect the anode from mechanical damage (Figure 24). Sausage anodes must be protected in split steel pipes with windows; these outer steel pipes must be lined with plastic pipe so as not to electrically short the anodes.

On the compartment side of the miter gate, two different approaches are possible. Individual button anodes can be mounted in each compartment or sausage anodes can be used. In present designs, sausage anodes are installed in protective steel pipes. The anode strings are inserted at the top and can be replaced by lock maintenance personnel as shown in Figure 25.

On an average miter gate leaf, the number of anode strings on the skin side can vary from 3 to 4. CERL's field investigations have shown that 4 anode strings spaced 10 to 15 ft (3 to 5 m) apart will provide adequate protection on the skin side (Figure 24). On the compartment side, each compartment should have a portion of the anode exposed. Enough anodes should be provided to polarize critical areas of the miter gates (e.g., the miter end and quoin end). These areas are critical for alignment purposes, since steel corrosion can lead to an early misalignment of the miter gate. The design procedures are discussed in TM 5-811-4.[12]

Some tainter gates are raised and lowered by chains (Figure 26). These chains corrode in the immersed zone, especially in the splash zone area. Corroded chains have been found to be frozen straight so that they would not wind well on the drums—it is common to see lock personnel beating on the chains with sledge

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[12]*Electrical Design, Corrosion Control*, TM 5-811-4 (Department of the Army, 1 August 1962).

36

Figure 23. Closeup of button anode at Cordell Hull showing blistering of vinyl paint (Nashville District).
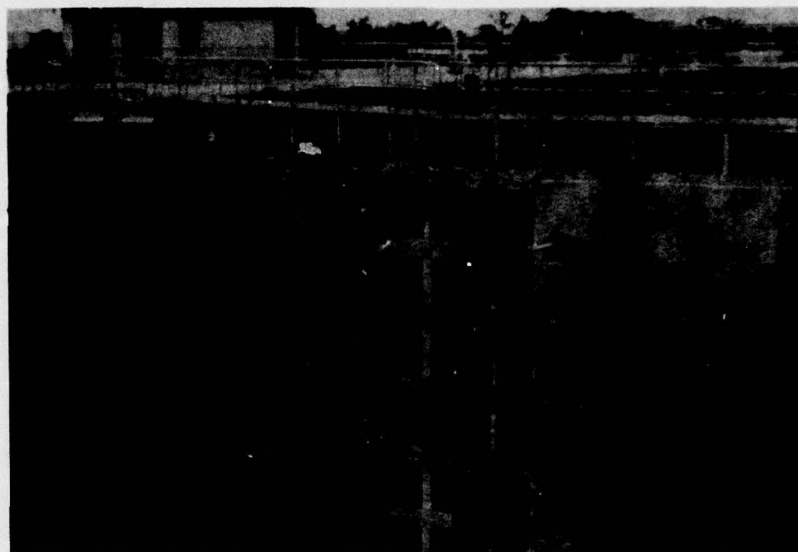
37

Figure 24. Port Allen Lock showing sausage anodes (New Orleans District).

Figure 25. Graphite anodes which can be spliced at the site (New Orleans District).

hammers to unfreeze them. Cathodic protection has also been attempted on chains by placing a magnesium ribbon on some of the chains (Figure 27). In later designs, stainless steel cables were used. Stainless steel is cathodic to carbon steel, which means that galvanic action will cause a scratched carbon steel area near a stainless steel cable to corrode faster. Sacrificial cathodic protection can be used in such cases to provide local protection. At one experimental installation (Hilderbrand Lock and Dam in Pittsburgh District), a section of stainless steel chain has been used to replace the old carbon steel chain (Figure 28). CERL is monitoring the performance of this prototype installation.

Cathodic protection of tainter gates was attempted by Rhowedder and Shanks at the Rock Island District in the 1950s.[13] These gates have skin plates on both the upstream and downstream sides. The outer surfaces on the upstream side are curved (Figure 29); therefore, it was necessary to mount the sausage anodes in a horizontal direction. The downstream side has extreme water turbulence (Figure 30), which means only button anodes would be effective. However, since button anodes were not available in the 1950s, only rod anodes were used (unsuccessfully).

The inside of the tainter gates can be easily protected because there is no straying. Approximately two-thirds of the inside surface is dry and must be protected by paint. The lower third of the inside, which is immersed in water and difficult to paint, can have a supplemental sacrificial or impressed-current cathodic protection system to prolong the life of the coating.

Magnesium anodes have been used by the Tulsa District for the protection of tainter gates on the Arkansas River. Tainter valves, which are used to fill a lock chamber, are immersed in water and have high velocity water flowing near the edges. Cathodic protection has been attempted for such structures by Tulsa District. However, the mounting of the anodes and their replacement has posed a problem.

Floating mooring bits (Figure 31) are made of hollow carbon steel which travels on stainless steel rollers. Some of the mooring bits on the Ohio River Division had developed corrosion pits which make the floating mooring bit sink to the bottom of the lock. Cathodic protection has been achieved by spacing a spiral magnesium ribbon 20 in. (508 mm) apart on the mooring bit. The "throw distance" of the magnesium ribbon

anode was determined in the laboratory by electric current field plots (Figure 32). Mooring bits made of stainless steel are also being considered. CERL will monitor the performance of these prototype installations.

Criteria of Cathodic Protection

NACE standard RP-01-69 gives the recommended practice for controlling external corrosion on underground or submerged metallic systems. The standard also details the criteria for cathodic protection. These criteria are applicable to immersed steel structures and are as follows:

1. A negative (cathodic) voltage of at least 0.85 volt as measured between the structure surface and a saturated copper-copper sulphate reference electrode containing the electrode. Determination of this voltage is to be made with the protective current applied.

2. A minimum negative cathodic voltage shift of 300 mV, produced by the application of protective current. The voltage shift is measured between the structure surface and the stable reference electrode contacting the electrolyte. This criterion of voltage shift applies to structures not in contact with dissimilar metals.

3. A minimum negative (cathodic) polarization voltage shift of 100 mV measured between the structure surface and the stable reference electrode contacting the electrolyte. This polarization voltage shift is determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage reading after the immediate shift shall be used as a base reading from which the measure of polarization decay is made.

4. A structure-to-electrolyte voltage at least as negative (cathodic) as that originally established at the beginning of the Tafel segment of the E-logI curve.* This structure-to-electrolyte voltage shall be measured between the structure surface and the stable reference electrode contacting the electrolyte in the same location where voltage measurements were taken to obtain the E-logI curve.[14]

[13] J. L. Rhowedder and F. W. Shanks, *Cathodic Protection Investigation*, CWI No. 311 (U.S. Army Corps of Engineers Rock Island District, March 1954).

[14] *Recommended Practice for Control of External Corrosion*, RP-01-69 (NACE, 1969).

*E-logI curve is the polarization curve of the structure. Current is applied to shift the potential of the structure to a more negative or cathodic direction. The linear portion of the potential (E) vs log current (logI) plot is called the Tafel segment.
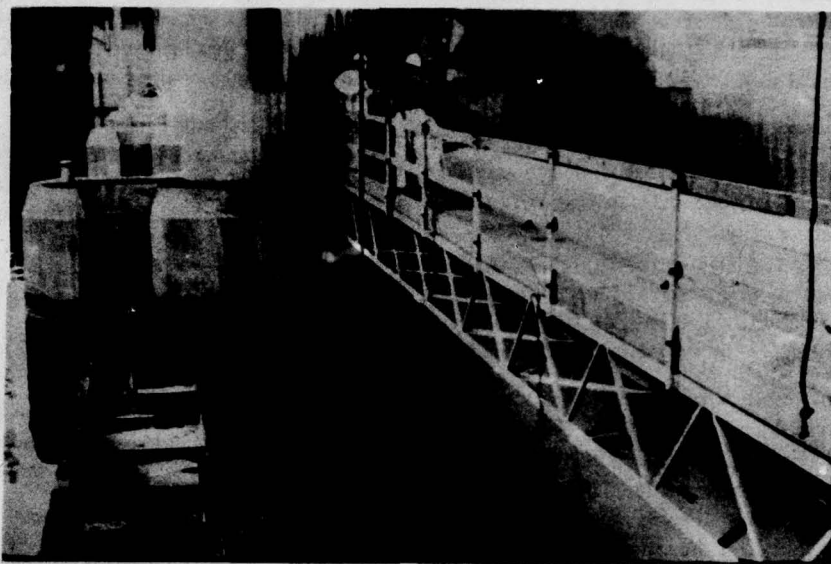
Figure 26. The tainter gates are raised by chains on Ohio River, as well as on Mississippi River locks and dams.
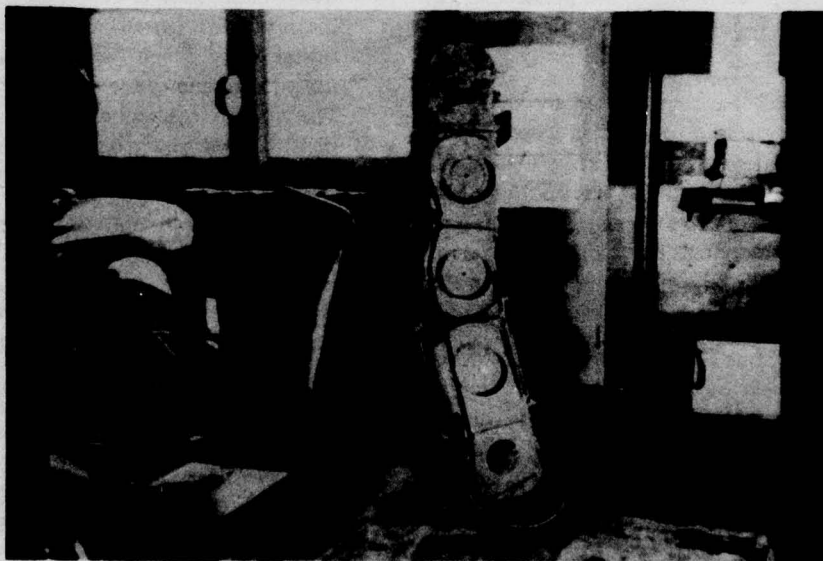
Figure 27. Experimental cathodic protection of tainter gate raising chains at Rock Island District.
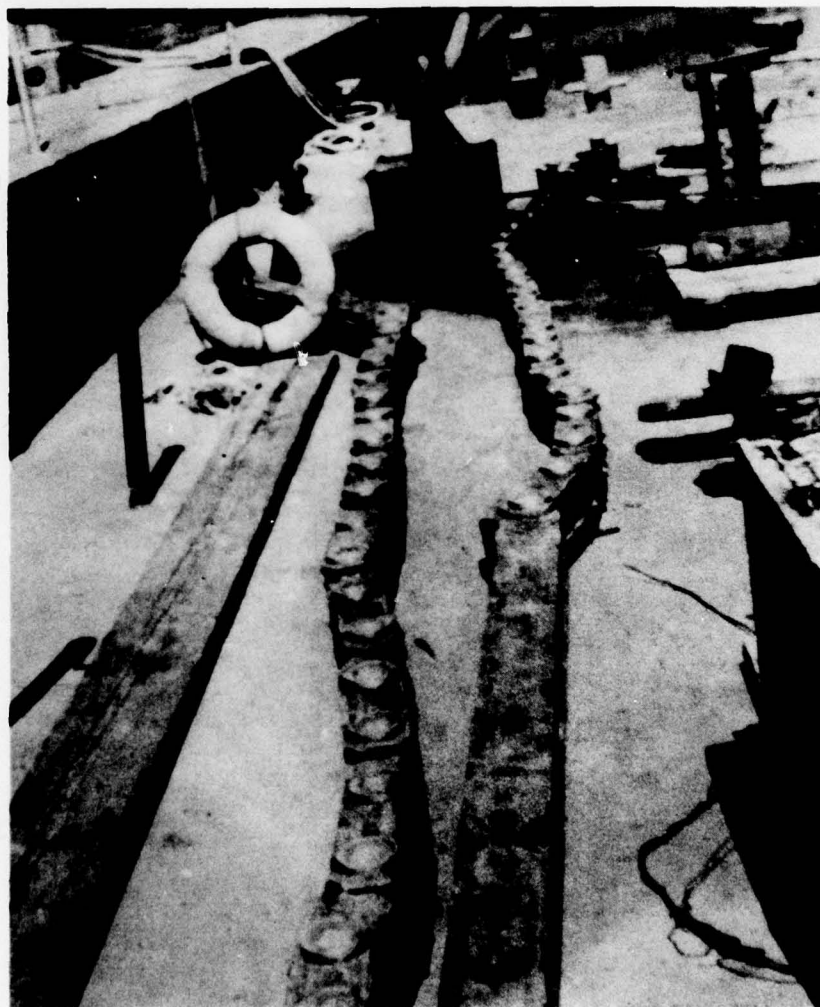
Figure 28. Tainter gate raising chains made from stainless steel (Carpenter 450) at Hilderbrand Lock and Dam, Pittsburgh District.

41
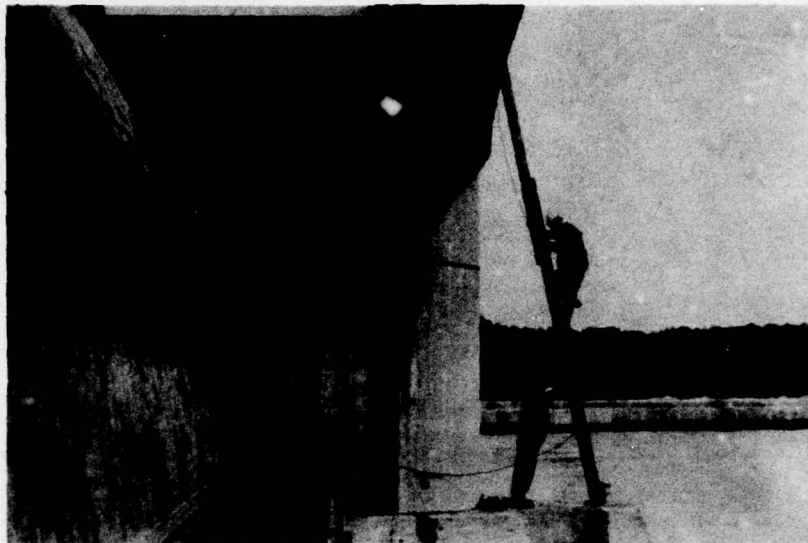
Figure 29. Front side of tainter gate at Cheatham Lock and
Dam showing corrosion pits (Nashville District).

Figure 30. Back side of tainter gate where corrosion is caused
by high-velocity swirling water and debris.

42
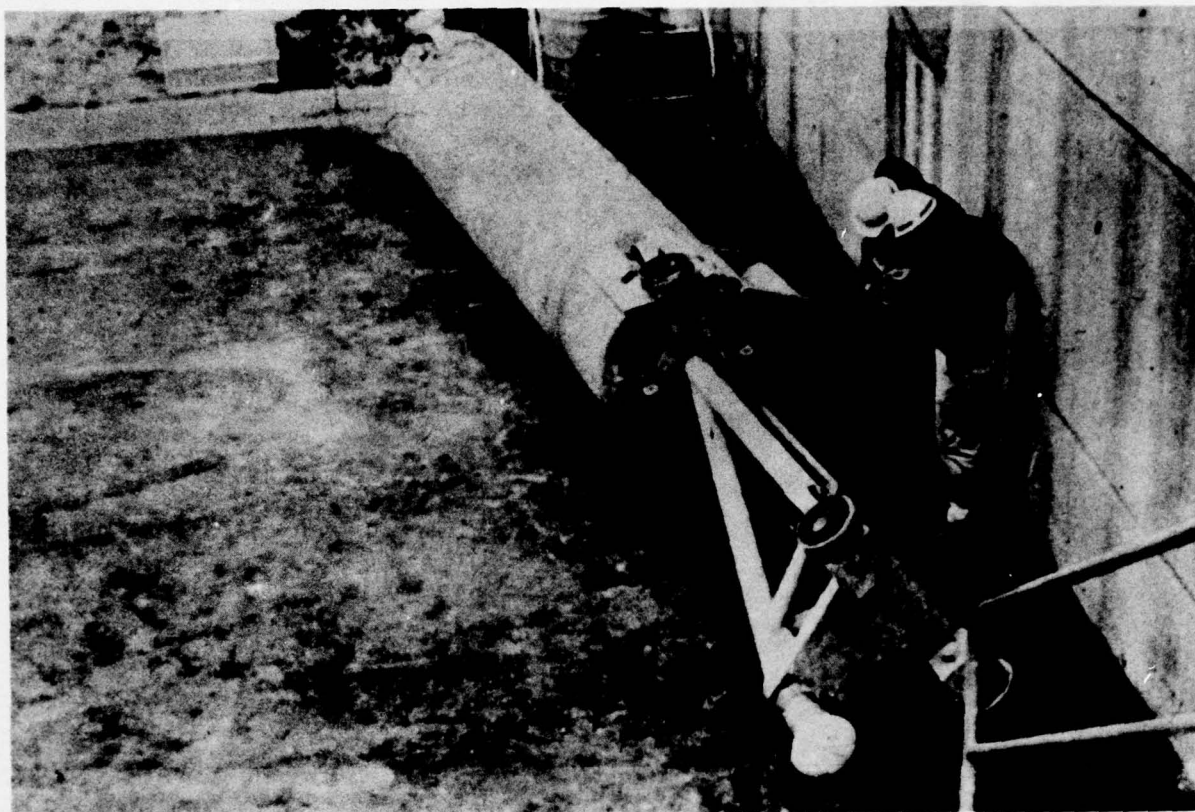
Figure 31. Floating mooring bit.

5. A net protective current from the electrolyte into the structure surface as measured by an earth current technique applied at predetermined current discharge points on the structure.

In hydraulic structures, the most readily used criterion is the negative 0.85 V with respect to copper-copper sulphate cell. For field application, a high resistance (100,000 ohms/V) voltmeter is used; the negative lead of the voltmeter is connected to the structure and the positive is connected to a copper-copper sulphate reference cell which is dropped in the water. The reference cell is brought as close to the structure as possible. Since the reference cell cannot be brought in close contact with the structure because of water turbulence, IR drop in the water must be considered.

Sometimes the second criterion, the 300 mV shift, is also used for CE structures; however, it is very difficult to determine the preprotection potential. For example, if the preprotection potential of the structure is −0.45 V with respect to copper-copper sulphate cell, there is no need to polarize the structure to −0.85 V. A reading of −0.75 V will signify complete cathodic protection. To measure the preprotection potential of the structure, the cathodic protection system will have to be shut off for approximately a week to allow depolarization to occur. Preprotection potential can also be measured before the cathodic protection system is installed and turned on.

In the third criterion, the 100 mV decay, the rectifier is shut off and the potential of the structure drops immediately, e.g., from −0.85 to −0.75 V. If the

43
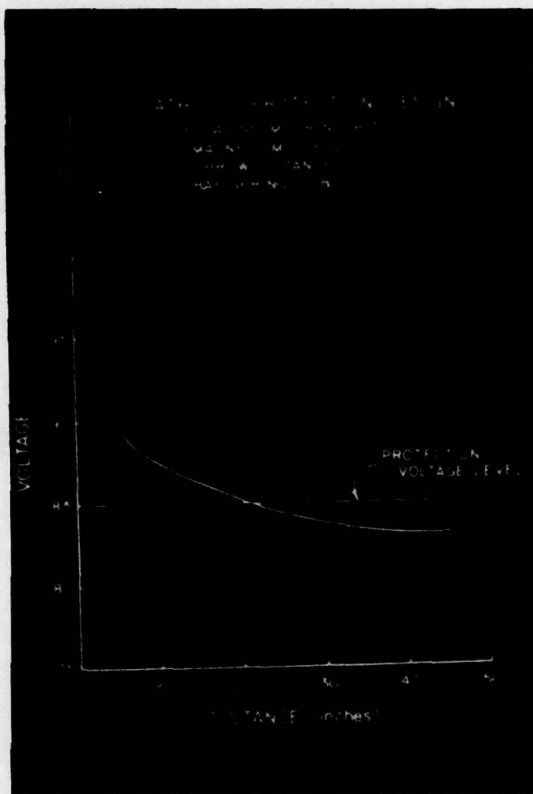
Figure 32. Electric current field plots of sacrificial cathodic protection by magnesium ribbon.

potential then decays to −0.65, a polarization decay of 100 mV is achieved. This criterion can be used in CE hydraulic structures, but it has not been exploited yet.

The remaining two criteria proposed by NACE Standard RP-01-69 are too complex to be used under field conditions in CE hydraulic structures.

Another criterion which has been used in CE hydraulic structures is the presence of carbonate deposits. Carbonate deposits can be detected by squirting a dilute acid on the structure. If any effervescence is observed, it indicates that carbonate deposits have occurred as a result of cathodic protection current. Carbonate deposits on scratched area signify complete cathodic protection. This criterion can only be used for local areas since most of the structures are under water and cannot be reached.

Experiments conducted at CERL have shown that the corrosion rate of steel can be reduced to zero if

the potential of the bare steel is shifted to −0.85 with reference to a copper-copper sulphate reference cell. The corrosion rate reduces logarithmically with a shift in potential in the negative direction. Therefore, any potential shift in the cathodic direction (more negative with respect to copper-copper sulphate reference cell) will decrease the corrosion rate logarithmically. A detailed discussion is presented in Chapter 3.

3 VELOCITY EFFECTS IN CATHODIC PROTECTION

General

The effect of water velocity on the current required for cathodic protection was investigated by CERL since previous studies had shown that the corrosion rate of steel in water increases as a function of water velocity (Figure 33).[15] This is consistent with the fact that oxygen availability controls the corrosion rate of iron and steel in water—water flow reduces the thickness of the stagnant layer on the metal surface and thereby supplies more oxygen to cathodic sites. Figure 34 is a schematic of typical polarization curves of steel in water. The shape of the cathodic polarization curve determines the current requirement for cathodic protection. The external current needed to maintain a certain cathodic potential varies inversely with the steepness of the cathodic polarization curve. The unavailability of oxygen in quiet water appears as pronounced cathodic polarization in Figure 34a. The effects of water velocity on polarization are shown in Figure 34 a to d.

Since the horizontal current axis in potential current plots is generally a log scale, the current requirement for cathodic protection increases quite markedly with water velocity (v). It has been observed that the corrosion rates follow a $\sqrt{v}$ relationship.[16]

[15]H. H. Uhlig, *Corrosion and Corrosion Control* (John Wiley and Sons, Inc., 1963), p. 109; J. R. Chin and K. Nobe, "Effect of Oxygen and Benzotriazole on the Corrosion Characteristics of Rotating Iron District Electrodes in Acidic Chloride Solutions," *Corrosion*, Vol 33 (1977), pp 364-369; J. Perkins, K. J. Graham. G. A. Storm. G. Leumer, and R. P. Schack, "Flow Effects on Corrosion of Galvanic Couples in Seawater," *Corrosion*, Vol 35 (1979), pp 22-32; and F. Mansfield and J. V. Kenkel, "The Effect of Velocity on Galvanic Corrosion of Aluminum Alloys, *Corrosion*, Vol 34 (1978), pp 376-386.

[16]J. Perkins, et al., "Flow Effects on Corrosion of Galvanic Couples in Seawater," *Corrosion*, Vol 35 (1979), pp 22-32.
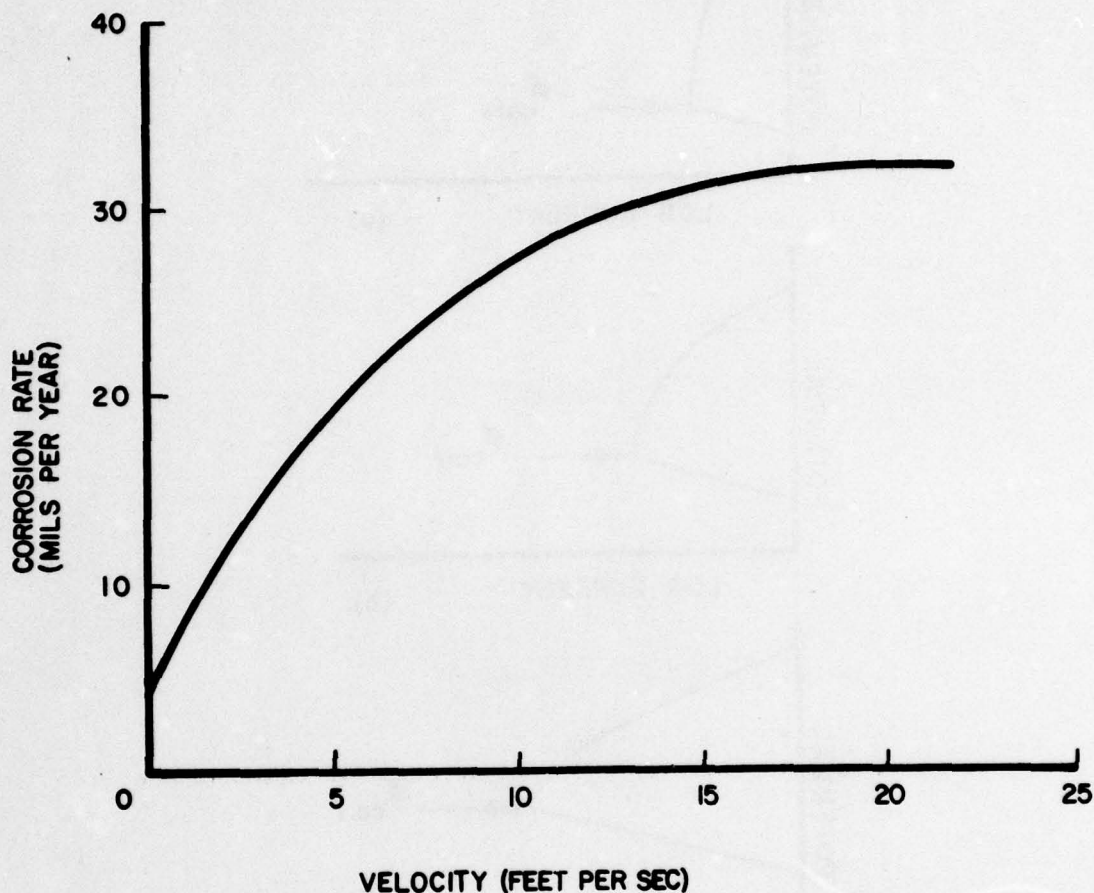
Figure 33. Seawater corrosion of steel vs water velocity.

The effects of dissolved oxygen on iron corrosion were also considered. Factors influencing the solubility of oxygen in aqueous solutions are of major importance. The solubility of oxygen *increases* with oxygen partial pressure, but *decreases* approximately 2 percent/°C.

Experimental Procedure

Experiments were conducted to determine the effect of bare steel area and water velocity on cathodic protection current requirements. A schematic diagram of the area effect experiments is shown in Figure 35. All measurements were conducted in insulated plastic containers and reference calomel electrodes were used. A Princeton Applied Research Potentiostat was used to maintain constant potential of the specimen with reference to the calomel standard electrode. It was determined by weight loss experiments (Figure 36) that complete cathodic protection is provided if a bare steel plate is maintained at a potential of −0.774 with respect to a calomel reference half cell in this media. This corresponds to a value of −0.85 V with respect to copper-copper sulphate reference cell.

All freshwater tests were conducted in tap water (Table 4). An equilibrium air concentration was provided by bubbling air through the water for the larger 1 sq ft specimen. The air inlet hose was connected to a fritted disc, which was placed behind the counter electrode to avoid velocity effects caused by bubbling
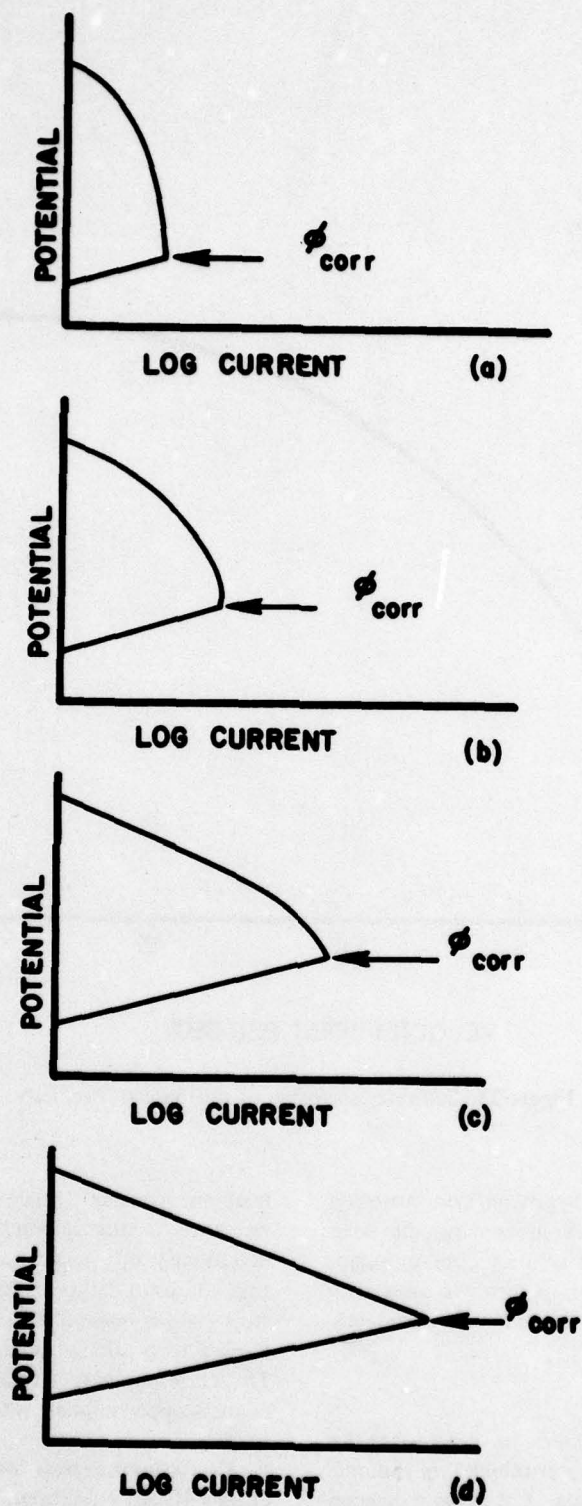
Figure 34. Schematics of the variations of cathodic polarization with water velocity. The X axis shows log current; ϕ_{corr} is the corrosion potential (the water velocity is increasing from a to d).

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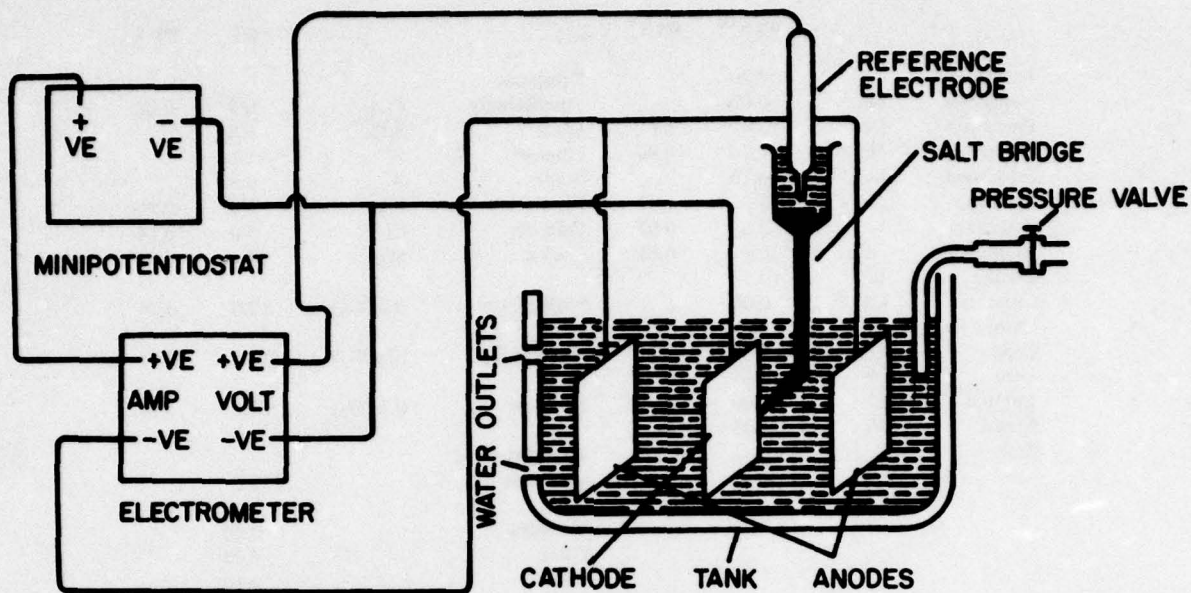
Figure 35. Test setup for cathodic protection experiments.

$$MPY = \frac{534\,W}{DAT}$$

W = WEIGHT LOSS, MG
D = DENSITY OF SPECIMEN, G/CM
A = AREA OF SPECIMEN, SQ IN.
T = EXPOSURE TIME, HR

Figure 36. The completeness of protection criteria required
for cathodic protection in tap water.

Table 4
Mineral Analysis of Tap Water*

		mg/ℓ**	me/ℓ+				mg/ℓ	me/ℓ
Iron (total)	Fe	0.00		Phosphate				
Manganese	Mn	0.00		(unfiltered)	PO₄		0.0	0.00
Calcium	Ca	13.6	0.68	Silica	SiO₄		6.8	
Magnesium	Mg	11.7	0.96	Fluoride	F		1.1	
Strontium	Sr	0.13		Boron	B		0.3	
Sodium	Na	32.9	1.43	Nitrate	NO₃		0.0	0.00
Potassium	K	2.6	0.07	Chloride	Cl		5.0	0.14
Ammonium	NH₄	0.9	0.05	Sulfate	SO₄		34.1	0.71
Barium	Ba	<0.1						
Cadmium	Cd	0.00		P Alkalinity	(CaCO₃)		12.0	0.24
Chromium	Cr	0.00						
Copper	Cu	0.00		M Alkalinity	(CaCO₃)		117.0	2.34
Lead	Pb	<0.05						
Lithium	Li	0.00		Hardness	(CaCO₃)		82.0	1.64
Nickel	Ni	<0.05						
Zinc	Zn	0.00		Total Dissolved				
				Minerals			179.0	
				Turbidity			0.00	
				Color			0.00	
				Odor			0.10	
				Temperature (at tap)			11.7°C	
				pH (in lab)			9.0	

*Analysis conducted by the laboratory of the Illinois State Water Survey, Champaign, IL.
**mg/ℓ = milligrams per liter
+me/ℓ = milliequivalents per liter; mg/ℓ × 0.0583 = grains per gallon

air. Stainless steel counter electrodes were used. Flat counter electrodes were used for flat specimens. All experiments were conducted at room temperature (23°C). Specimens were made of ASTM A-36 steel 1/8-in. (0.125-mm)-thick plate. The front surfaces of the specimens were sandblasted and the back side prepainted to prevent the cathodic current from straying.

For the area exposure tests, specimens from 1 sq in. (64.5 mm²) up to 1 sq ft (0.09 m²) in cross section were used. Current readings were continuously plotted by automatic chart recorders. All the connections in the water were ins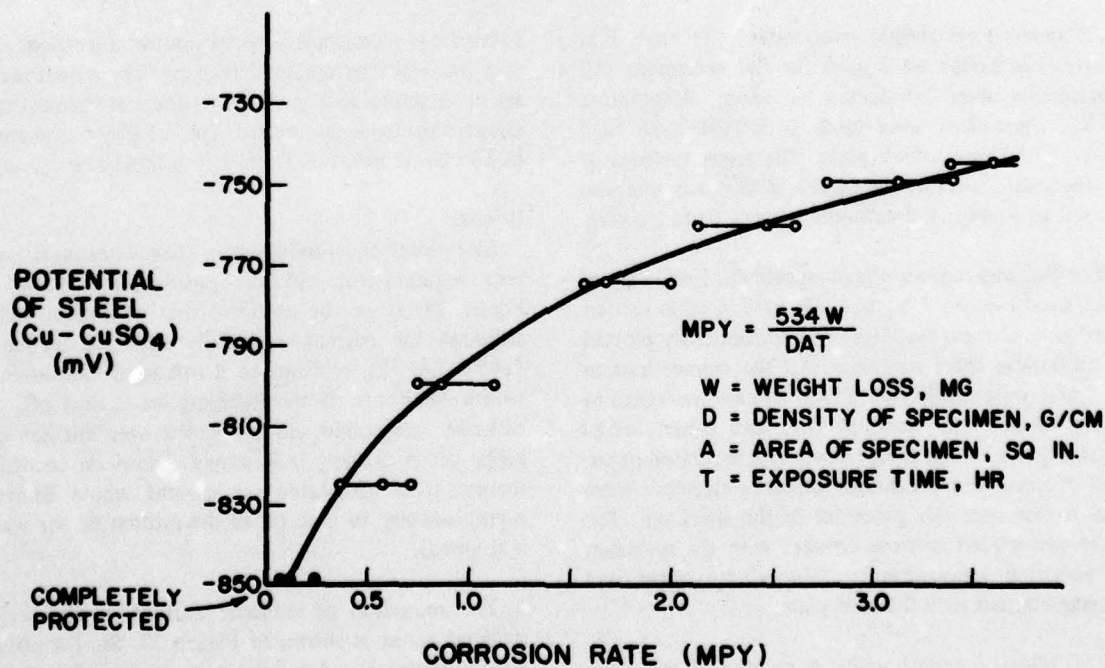ulated and special care was taken to totally insulate the specimen from any other foreign metallic piece. A salt bridge filled with saturated potassium chloride and a calomel reference electrode were used to measure the potential of the specimen. The probe was placed in close contact with the specimen for potential measurements. "Vycor" tips were used to make contact with the steel plate.

For velocity experiments, a cylindrical specimen with a surface area of 0.12 sq ft (0.01 m²) was used. The cylindrical anode was connected by a shaft and rotated by a constant velocity motor. Electrical contact was made by a copper bushing. The experimental set up is shown in Figure 37. Cylindrical stainless steel counter electrodes were used. The velocity was changed in 15-minute intervals from 0 to 4 ft/s (0 to 1.2 m/s).

Results

The effect of bubbling air in freshwater on the current required for cathodic protection is shown in Figure 38. It can be observed that in aerated water, although the current is initially high (20 mA/sq ft [215 mA/m²]), it drops to 2 mA/sq ft (22 mA/m²) within 48 hours. If the bubbling air is shut off, the cathodic protection current drops even further and keeps on decreasing indefinitely. Based on corrosion theory, it is postulated the current would decrease asymptotically to zero (if all the motion of the water is stopped).

The reduction of cathodic current in nonaerated stagnant water is shown in Figure 39. Similar effects were observed in 3.5 percent sodium chloride solution (Figure 40). The current required for cathodic protection in salt water is approximately 30 mA/sq ft (323

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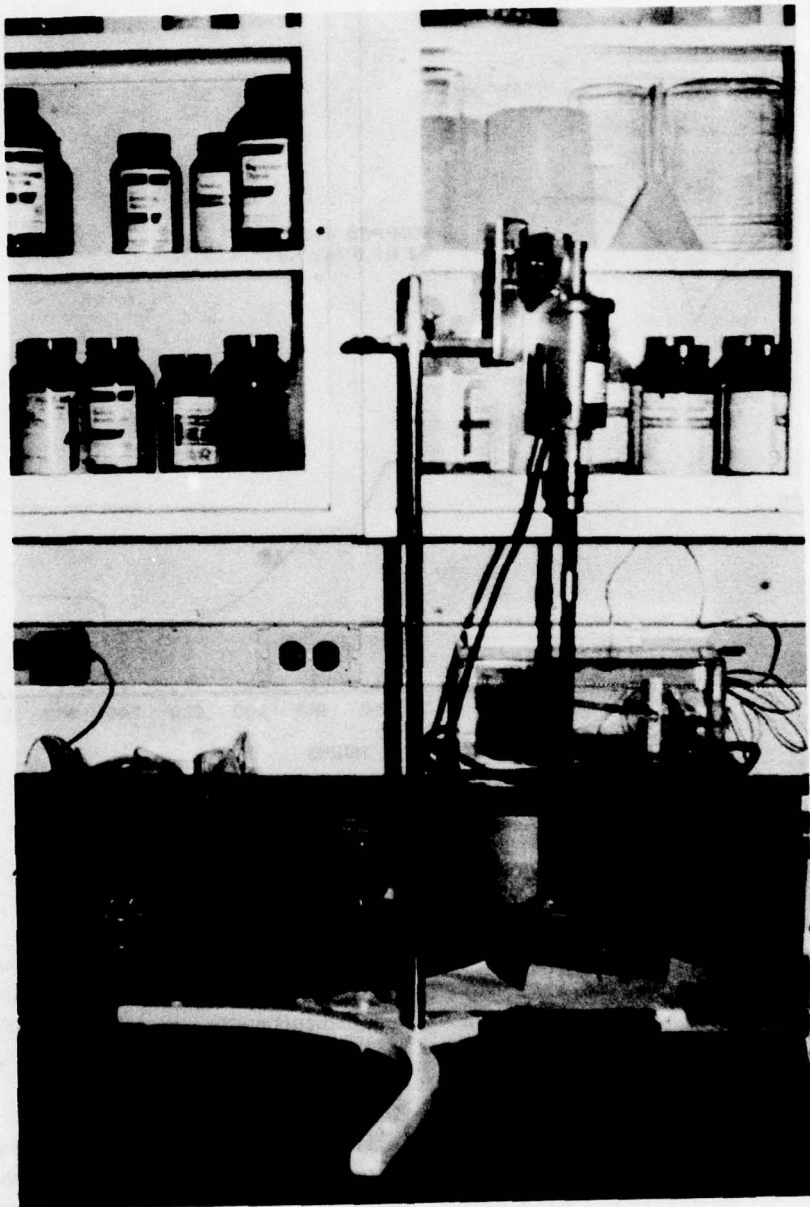
Figure 37. Laboratory experimental set up for tests to determine
the effect of velocity on cathodic protection current.
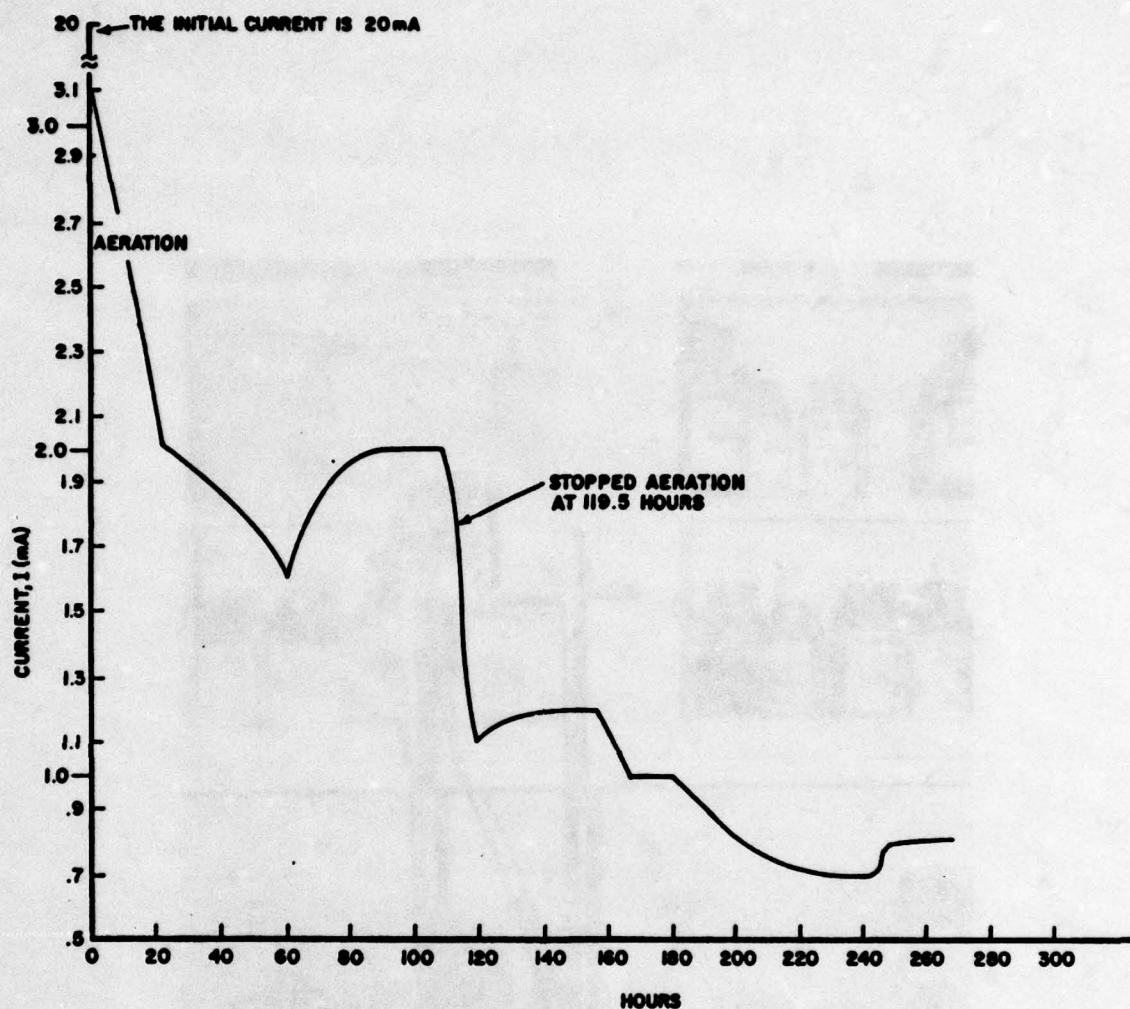
Figure 38. Current requirements for 1 sq ft (0.09 m^2) of bare steel in tap water with and without aeration; E$_c$ = −0.774 V (calomel). E$_c$ signifies constant cathodic protection voltage maintained by the potentiostat.

mA/m^2) and decreased to 12 mA/sq ft (129 mA/m^2) in 180 hours. Again, if bubbling is stopped, water stagnates and the current required for cathodic protection keeps on decreasing asymptotically to zero (if all the motion of the water is stopped).

All of these experiments were conducted on 1 sq ft (0.09 m^2) of bare steel plate with a painted backsurface and the potential was maintained at −0.774 with respect to calomel. Weight loss experiments have shown that complete protection is achieved when the potential of the specimen is maintained at −0.774 with

respect to calomel reference electrode. Results on the effect of the area of the steel surface on current requirements are shown in Figure 41. For 1 sq ft (0.09 m^2) of bare steel area, the current is 2 mA/sq ft (22 mA/m^2) in freshwater.

The effect of velocity on the cathodic protection current is shown in Figure 42. It was observed that the impressed-current requirements increased with velocity. The increase in velocity reduces the thickness of the stagnant layer at the metal surface and supplies more oxygen to the cathodic sites. Because the transport of

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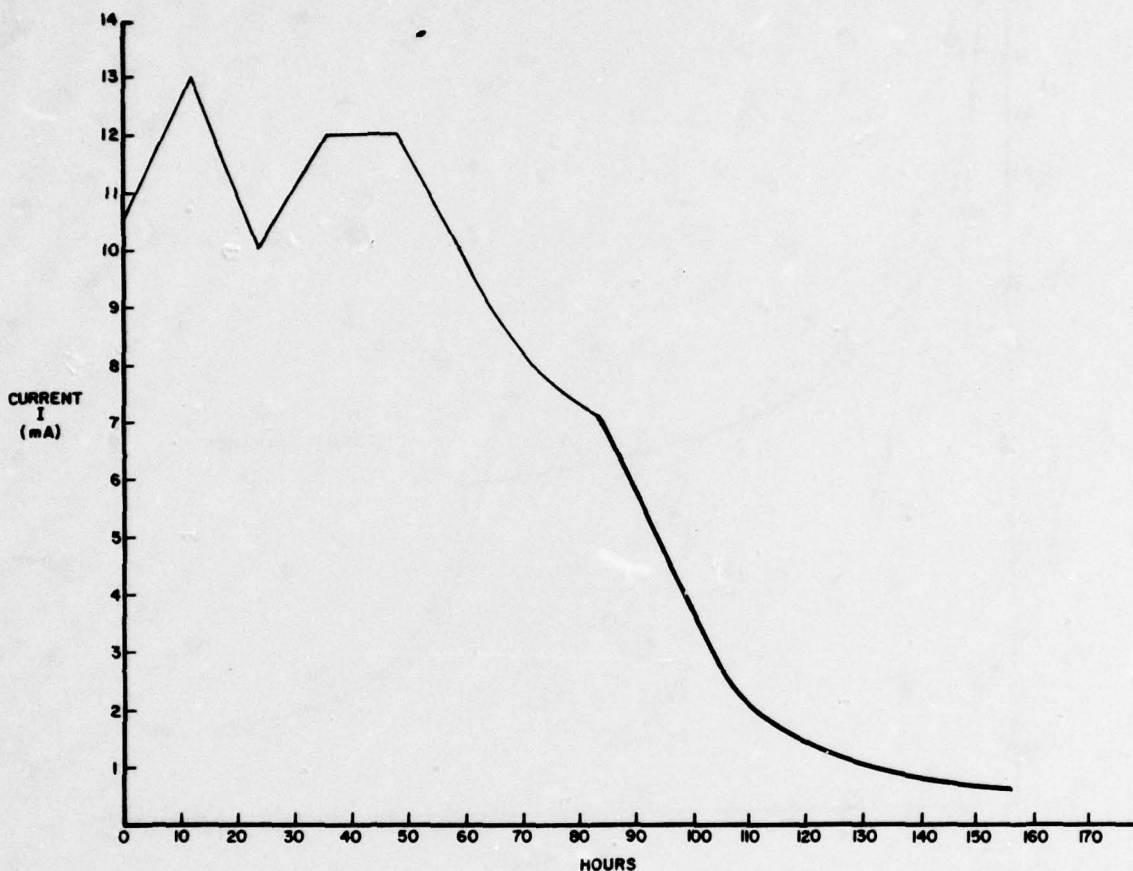
Figure 39. Current requirements for 1 sq ft (0.09 m^2) in stagnant tap water without aeration; $E_c = -0.774$ V (calomel). E_c signifies constant cathodic protection voltage maintained by the potentiostat.

oxygen is a diffusion-controlled reaction,[17] a square root dependence of cathodic protection current on velocity is expected (Figure 42). This relationship can be used to estimate current requirements at higher velocities. The current required for cathodic protection is a function of time; Figure 43, then, represents the current requirements when the velocity was changed at 15-minute intervals.

[17]J. R. Chin and K. Nobe, "Effect of Oxygen and Benzotriazole on the Corrosion Characteristics of Rotating Iron District Electrodes in Acidic Chlorine Solutions," *Corrosion*, Vol 33 (1977), pp 364-369; J. Perkins, et al., "Flow Effects on Corrosion of Galvanic Couples in Seawater," *Corrosion*, Vol 35 (1979), pp 22-32; and F. Mansfield and J. V. Kenkel, "The Effect of Velocity on Galvanic Corrosion of Aluminum Alloys," *Corrosion*, Vol 34 (1978), pp 376-386.

The cathodic reaction in aerated waters consists of reduction of oxygen which reaches a limiting current I_L:

$$I_L = K \frac{C(O_2) \cdot D}{\delta} \qquad \text{[Eq 2]}$$

I_L depends on the concentration of oxygen $C(O_2)$, the diffusion coefficient of oxygen (D), and the thickness of the diffusion layer (δ). Stirring of the water or rotating the specimen decreases δ and increases the current. When the rotation is increased further, the corrosion reaction can eventually become charge-transfer controlled and reach a constant value. Based on this hypothesis, one would expect to see the cathodic protection polarization current increase with water veloc-

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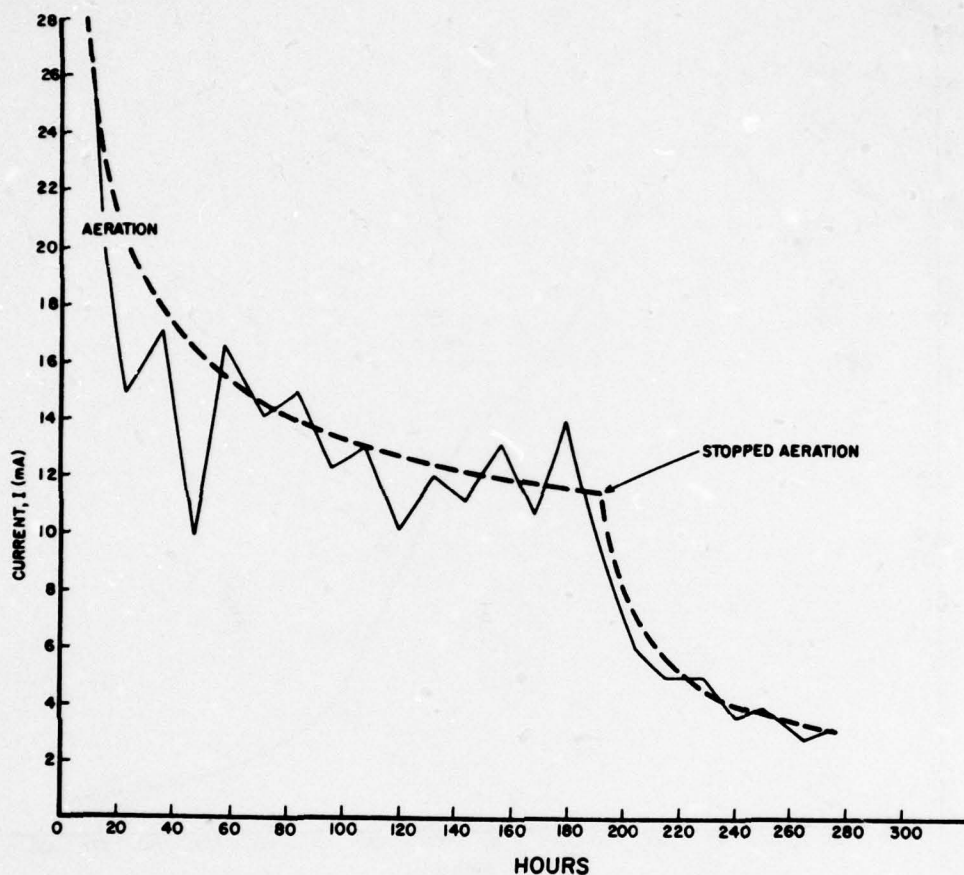
Figure 40. Current requirements for 1 sq ft (0.09 m^2) of bare steel in 3.5 percent NaCl solution with and without aeration; E_c = −0.774 (calomel). E_c signifies constant cathodic protection voltage maintained by the potentiostat.

ity in a square root manner ($\sqrt{v}$) and reach a constant saturation value. The saturation current density has not been measured because of experimental limitations at this time.

4 PLATINIZED ANODES

The usefulness of platinum as an inert electrode material in a variety of other electrolyte processes is well known. In cathodic protection, the useful properties of platinum are exploited, but the volume and cost of platinum are kept to a minimum by using titanium and niobium as substrate materials.[18] Titanium and niobium have exceptional resistance to most corroding media because they form an inert surface oxide film. However, because of this film, titanium and niobium, by themselves, will not readily pass current when used as anodes in water. But a deposition of an

[18]R. Baboian, "Platinum Consumption in Cathodic Protection Anodes," *Materials Performance*, Vol 16 (1977), pp 20-23; R. Baboian, "New Developments in Platinum Type Anodes," *Materials Performance*, Vol 18 (1979), pp 9-15; and M. A. Warne, *Precious Metal Anodes, the Options for Cathodic Protection*, Paper No. 142, presented at the 1978 Corrosion Conference, Houston, TX (March 1978).

Figure 41. Electrochemical experimentation on cathodic protection.

Titanium can be forged, bent, cut, stamped, extruded, and successfully welded, making possible a large variety of electrode shapes that can be manufactured. Both titanium and platinum have a strong resistance to abrasion. The use of platinized titanium as an anode material has been attempted since 1958 in commercial installations in England.

Platinized titanium and niobium anodes can operate at very high current densities; thus, it is generally necessary to use only a small anode and only a relatively small area needs to be platinized. Standard platinum thickness is 100 μin. (0.003 mm); however, thickness from 50 to 250 μin. (0.001 to 0.006 mm) can be used. The consumption rate of the platinized anode is 6 mg/A-year. In most seawater installations, current densities of about 100 A/sq ft (1076 A/m^2) are generally used. The upper limit is usually 200 A/sq ft (2152 A/m^2). A 1/4-in. (6-mm)-diameter titanium rod with 100-μin. (0.003-mm) platinum has a life of 50 A-years/ft (164 A-years/m).

Platinized titanium has been used for cathodic protection of ships, submarines, and for internal protection of pumps for cooling tower systems. It has also been used for the protection of heat exchangers.[19] Some platinized titanium anodes have failed for reasons other than platinum consumption. Titanium substrates can be attacked by chloride or by overacidic conditions. Fatigue fracture of the anode from underdesign has been caused by underestimating cantilever loading effects in some heat exchanger designs.

Titanium, niobium, and tantalum are metals that form dielectric oxide films when made as an anode in a cathodic protection circuit. The cost of niobium materials is 10 times the cost of titanium. Tables 5, 6, and 7 show the electrical and mechanical properties and costs of titanium, niobium, and tantalum substrates. The applications of niobium and tantalum as substrate materials have been exploited in marine work. Since niobium is considerably cheaper than tantalum, the use of the latter as a substrate material for platinum is rare.

extremely thin layer of platinum only a few millionths of an inch thick on the surface will allow current to flow from the substrate, through the platinized areas, and into the water. If titanium or niobium surfaces are exposed, they remain inactive at normal impressed voltages. These materials form films which act like valves; i.e., in case the platinum surface gets scratched, the anode stops passing current from the scratched area. This occurs because the protective oxide film which forms on the surface only breaks down at voltages on the order of 60 V for titanium and 100 V for niobium in freshwater. These voltages are well above the normal operating cathodic protection voltages. Thus, both titanium and niobium substrates can be used as anode materials in freshwater.

In chloride-containing solutions, the breakdown voltage for titanium is reduced considerably (approximately 8 V), yet the breakdown voltage for niobium remains at approximately 100 V, which makes titanium substrates *unsuitable* for use in salt water or brackish water cathodic protection systems. In chloride-containing water, only platinized niobium can be used. Nevertheless, in freshwater, titanium forms a valuable substrate for platinum; the composite is characterized by good mechanical toughness and long life.

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[19]R. Baboian, "Platinum Consumption on Cathodic Protection Anodes," *Materials Performance*, Vol 16 (1977), pp 20-23; R. Baboian, "New Developments in Platinum Type Anodes," *Materials Performance*, Vol 18 (1979), pp 9-15; and M. A. Warne, *Precious Metal Anodes, The Options for Cathodic Protection*, Paper No. 142 presented at the 1978 Corrosion Conference, Houston, TX (March 1978).
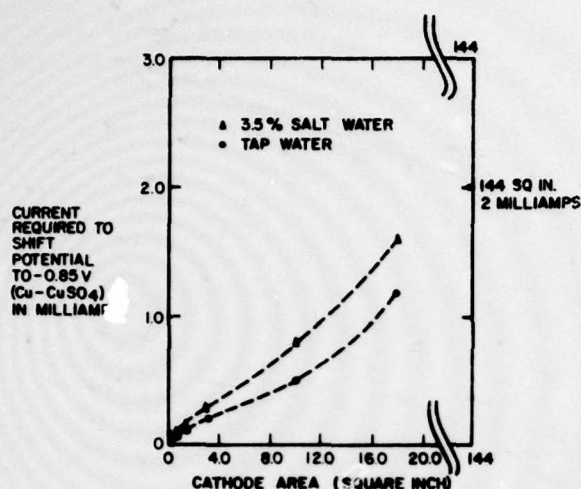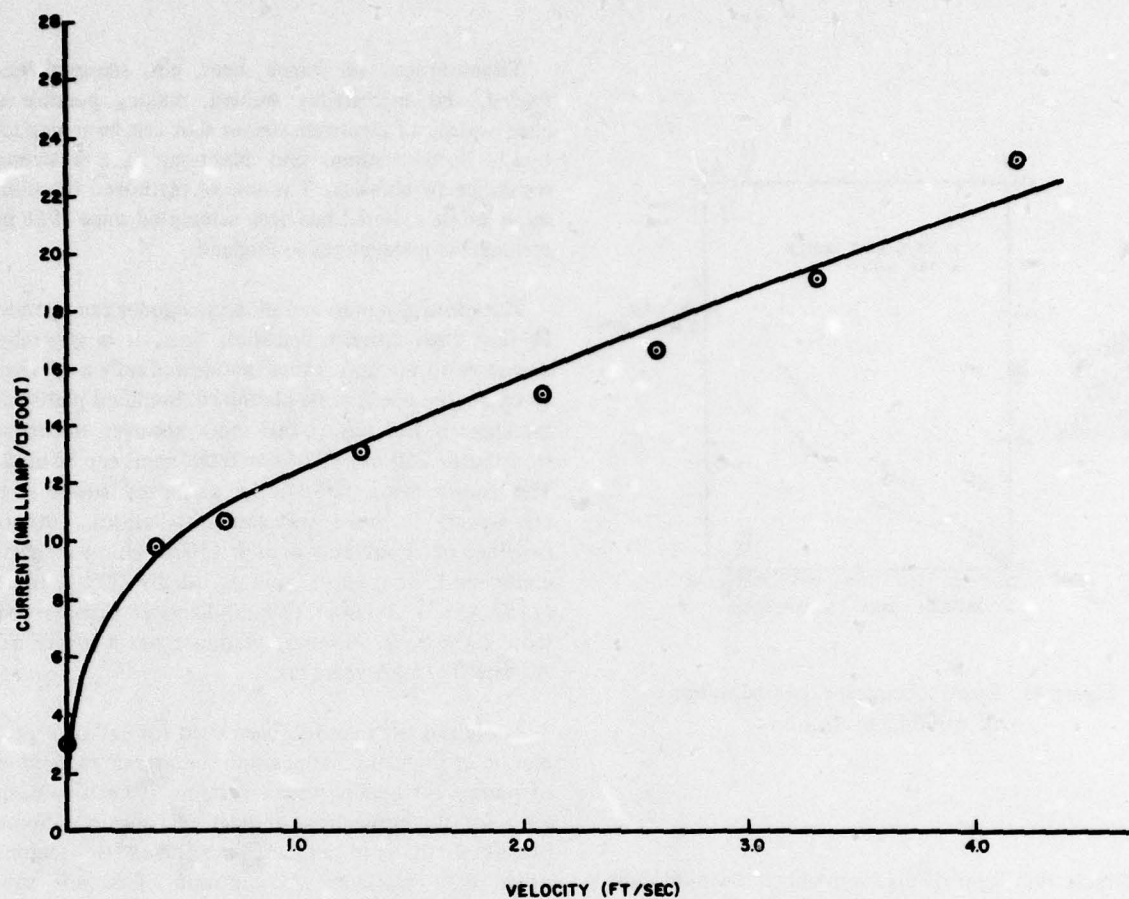
Figure 42. Effect of water velocity on current requirements for a bare steel cylinder 0.12 sq ft (0.011 m^2) area; E$_c$ = −0.774 (calomel). E$_c$ signifies constant cathodic protection voltage maintained by the potentiostat.

Table 5
Resistivities of Anode Substrates

	Electrical Resistivity (ohm-cm, 20°C)
Titanium	48
Niobium	15
Aluminum	2.7
Copper	1.7

Table 6
Mechanical Properties

	Titanium	Niobium	Mild Steel
Density (gm/cc)	4.51	8.6	7.9
0.2% proof stress N/mm^2 (tsi)	200–460* (13–30)	96–517+ (6–33+)	240–290 (15–18)
Ultimate Tensile Strength N/mm^2 (tsi)	290–730* (19–47)	224–576+ (14–37)	360–550 (25–35)
Elongation on 50 mm (%)	15–25*	15–53+	20–25
Hardness (DPN) Annealed	110–160*	60	130
Worked (typical)	240	200	--

*Dependent on grade
+Dependent on composition and amount of cold work

54

Table 7
Comparison of Substrate Materials

Substrate Material	Voltage Capability	Strength	Conductivity	Ease of Making Connections	Cost
Titanium	Low*	High	Low+	Moderate++	Moderate
Niobium	High	Moderate**	Moderate+	Poor+	High

*Eight to ten volts in chloride but 60 to 80 volts in low chloride waters. High (more than 40 V) in back-fill applications.

**Can be improved by mechanical working or by incorporation of steel at some loss in overall integrity.

+Can be improved in appropriate cases by incorporation of copper at some loss in overall integrity.

++Can be eased by using copper cores/claddings; mechanical joints require surface treatment for best results.
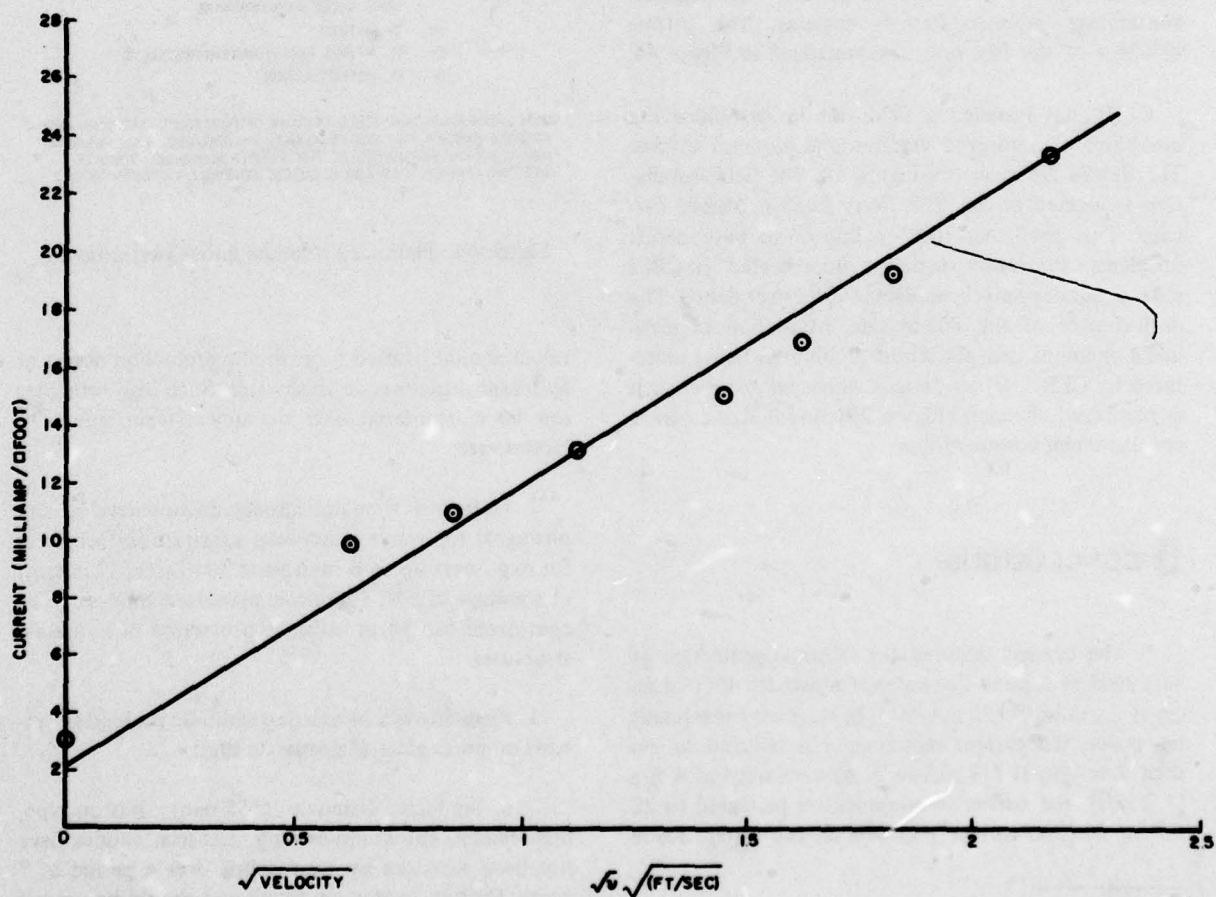
Figure 43. Effect of water velocity on current requirements for bare steel cylinder 0.12 sq ft (0.011 m^2) area; E$_c$ = –0.774 (calomel). E$_c$ signifies constant cathodic protection voltage maintained by the potentiostat. The velocity was increased in 15-minute intervals.

Metallurgically bonded platinum[20] has superior properties when compared to electroplated platinum. A nonporous, continuous layer of platinum is desirable because pores may be degradation sites where undercutting and spalling may occur.

CERL has conducted laboratory evaluation of 1/2-in. (12-mm) diameter platinized (electrodeposited) titanium anodes in tap water. In this anode, two 1-in. (25-mm) windows were ground out. One 1-in (25-mm)-long window was bare and the other window was painted with vinyl paint to simulate silt. Cathodic protection was applied at a current density of 10 mA/lin ft (33 mA/m) of the anode at 8 V. After 6 months of exposure, no pitting or any other reaction of the titanium surface was observed—the scratched surface was still shiny. Because of the large breakdown voltage of the titanium film, platinized anodes can be used in medium resistivity (4000 ohm-cm), nonchloride-containing, impressed-current systems. The pitting behavior of the titanium is summarized in Figure 44.

CERL has installed a field test to determine the durability of platinized titanium and niobium anodes. The details are shown in Figure 18. The field installation is located at the Mills Ferry Lock in Mobile District. This particular lock is known to have debris problems. Previously installed unprotected HSCBCI sausage anodes have been damaged by river debris. The performance of the side-by-side installation of platinized titanium and platinized niobium is being monitored by CERL. Other designs which are tougher such as platinized channels (Figure 20) mounted in a corner are also under consideration.

5 CONCLUSIONS

1. The current required for cathodic protection of bare steel in aerated tap water of resistivity 4000 ohm-cm is 2 mA/sq ft ($22 mA/m^2$). In stagnant (unaerated) tap water, the current requirement is reduced to less than 1 mA/sq ft ($11 mA/m^2$). At a velocity of 4 ft/s (1.2 m/s), the current requirement is increased to 22 mA/sq ft ($236 mA/m^2$) in aerated tap water. These

[20]R. Baboian, "New Developments in Platinum Type Anodes," *Materials Performance*, Vol 18 (1979), pp 9-15; and M. A. Warne, *Precious Metal Anodes, The Options for Cathodic Protection*, Paper No. 142, presented at the 1978 Corrosion Conference, Houston, TX (March 1978).
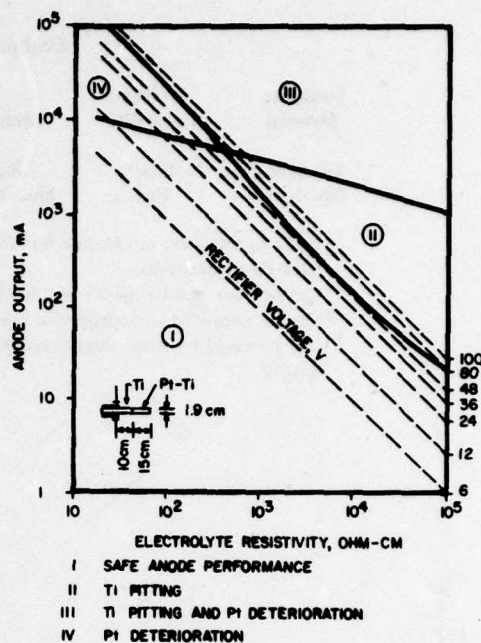

(FROM LABORATORY AND FIELD TESTING OF PLATINIZED TITANIUM AND NIOBIUM ANODES FOR POWER PLANT APPLICATIONS, BY G. NEKOKSA AND J. HANCK, PRESENTED AT THE ELECTROCHEMICAL SOCIETY MEETING [PACIFIC GAS AND ELECTRIC COMPANY, OCTOBER 1978]).

Figure 44. Platinized titanium anode performance.

values should be used for cathodic protection design of hydraulic structures in freshwater. Such high velocities can be encountered near the downstream side of a tainter gate.

2. Platinized titanium anodes do not develop any pitting in tap water at exposed substrate surface areas for exposures up to 6 months at 10 mA/ft (33 mA/m) at a voltage of 8 V. Therefore, platinized anodes can be considered for use in cathodic protection of hydraulic structures.

3. Field surveys of existing cathodic protection systems on miter gates demonstrate that:

a. Six-inch diameter (152-mm), button-type, high silicon, chromium-bearing, cast-iron anodes have not been damaged by river debris over a period of 7 years. Button anodes are tough and should be used if there is a debris or ice problem.

b. Marine-type graphite anodes have been softened by oxygen attack and should not be used.

c. Unprotected sausage anodes are susceptible to damage and should not be used when there is a debris problem.

d. Sausage anodes protected in steel pipes can be used if there is no ice problem.

CITED REFERENCES

Applegate, L. M., *Cathodic Protection* (McGraw-Hill Book Co., 1960).

Baboian, R., "New Developments in Platinum Type Anodes," *Materials Performance*, Vol 18 (1979), pp 9–15.

Baboian, R., "Platinum Consumption in Cathodic Protection Anodes," *Materials Performance*, Vol 16 (1977), pp 20–23.

Cable and Wire, Electrical (Power, Fixed Installation), Federal Specification J-C-30A and Am-1 (9 December 1974).

Chin, J. R. and K. Nobe, "Effect of Oxygen and Benzotriazole on the Corrosion Characteristics of Rotating Iron District Electrodes in Acidic Chloride Solutions," *Corrosion*, Vol 33 (1977), pp 364–369.

Circuit Breakers, Molded Case; Branch Circuit and Service, Federal Specification W-C-375B, Class 11b (22 July 1975).

Davy, H., "On the Corrosion of Copper Sheeting in Seawater and Methods of Preventing This Effect," *Philosophical Transactions*, Vol 114 (Royal Society, London, 1824), pp 151–158.

Design Considerations and Data for the Installation of Cathodic Protection of the Dalles Project Powerhouse Intake Gates, Report No. 3-201 (North Pacific Division, 1973).

Electrical Design: Corrosion Control, TM 5-811-4 (Department of the Army, 1 August 1962).

Electrical Plastic Tubing (EPT) and Conduit, EPC-40 and EPC-80, TC 2-1975 (NEMA, 1975).

Fontana, M. G. and N. P. Greene, *Corrosion Engineering* (McGraw-Hill Book Co., 1967).

Kearney, F. W., *Corrosion Control in Civil Works: Cathodic Protection*, Interim Report M-222/ADA045184 (Construction Engineering Research Laboratory [CERL], July 1977).

Mansfield, F. and J. V. Kenkel, "The Effect of Velocity on Galvanic Corrosion of Aluminum Alloys," *Corrosion*, Vol 34 (1978), pp 376–386.

Nylon Injection Molding and Extrusion Materials, ASTM Standard D 798-73 (American Society for Testing and Materials [ASTM], 1973).

Painting: Hydraulic Structures and Appurtenant Works, Guide Specification CW-09940 (Department of the Army, January 1977), pp 70–127.

Paint Manual—New Construction and Maintenance, Engineer Manual (EM) 1110-2-3400 (Department of the Army, 31 May 1967), pp 114–156.

Perkins, J., K. J. Graham, G. A. Storm, G. Leumer, and R. P. Schack, "Flow Effects on Corrosion of Galvanic Couples in Seawater," *Corrosion*, Vol 35 (1979), pp 22–32.

Recommended Practice for Control of External Corrosion, RP-01-69 (National Association of Corrosion Engineers [NACE] Standard, 1969).

Rhowedder, J. L. and F. W. Shanks, *Cathodic Protection Investigation*, CWI No. 311 (U.S. Army Corps of Engineers Rock Island District, March 1954).

Rock Island Corrosion Mitigation Course Notes (U.S. Army Corps of Engineers Rock Island District).

Standard for Specialty Transformers (National Electrical Manufacturer's Association [NEMA]).

Uhlig, H. H., *Corrosion and Corrosion Control* (John Wiley and Sons, Inc., 1963).

Warne, M. A., *Precious Metal Anodes, the Options for Cathodic Protection*, Paper No. 142, 1978 Corrosion Conference, Houston, TX (March 1978).

UNCITED REFERENCES

Bennett, L. H., J. Kruger, R. L. Parker, E. Pasaglia, C. Reimann, A. W. Ruff, and Y. Yakowitz, *Economic Effects on Metallic Corrosion in the United States,* Part I, Technical Report (National Bureau of Standards, May 1978).

Civil Works Corrosion Course Handout (U.S. Army Construction Engineering Research Laboratory [CERL], 1975).

Kearney, F. W., *Cathodic Protection Design for Brackish Water Systems: Freshwater Bayou Lock,* Technical Report M-235/ADA054307 (CERL, May 1978).

APPENDIX A:
INTAKE GATE AND HOIST CORROSION PROTECTION AT JOHN DAY DAM

General

The cathodic protection system at John Day Dam was intended to:

1. Protect the intake gates from galvanic corrosion between structural steel and the 410-steel roller chains, tracks, and embedded steel.

2. Stop corrosion of the 410 steel caused by active-passive cells.

3. Protect inaccessible compartments.

4. Prevent pitting of the hydraulic-hoist cylinder.

Cathodic protection for the dam's downstream gate face (except at the bottom) or the accessible upstream compartments was not considered necessary.

Basic Criteria

TM 5-811-4 and NPD Report No. 3-201 list the basic criteria for the John Day Dam cathodic protection system.[21] The NPD report contains the resistivity of the water in the Dalles pool, an average figure for anode-current drain, the current densities required for polarization, a figure for anode efficiency, and an assumed efficiency caused by crowding. Anode comparison factors were developed from the information in this report.

Provisions for Future Installation

There are 4-in. (101-mm) diameter drain holes in the girder which will allow anodes to be easily installed to protect the girder compartments if and when such protection is required.

Description of Protection System

Cathodic Protection Method

High-purity magnesium anodes were used. A rectifier was not seriously considered because not enough data were available on stray-current problems in the gate slot. Furthermore, the installation of a rectifier will be more difficult.

Current Densities

The 410 steel was polarized by applying a current density of 2.5 mA/sq ft (26 mA/m²). Structural-steel gate compartments that had poor accessibility received a current density of 0.25 to 0.5 mA/sq ft (2.6 to 5.1 mA/m²). The hydraulic cylinder and pipe, which was assumed to be well painted, received a current density of 0.25 mA/sq ft (2.6 mA/m²).

Intake Gate Anode Requirements

The gate was assumed to be in the raised position; Table A1 summarizes the anode requirements for one intake gate. All anodes were assumed to be 2-in. (50-mm) diameter rods. These anodes were selected instead of small sizes because they had a longer service life and required less hardware and labor to install. For example, the required lengths of 1.561- and 1.315-in. (40- and 33-mm) diameter anodes were 794 and 925 ft (242 and 282 m), respectively, for the same current option. Figure A1 shows the location of the anodes on the gate.

Hydraulic Hoist Cylinder Anode

A single run of 1-in. (25-mm) diameter anode 50 ft (15 m) long paralleled a 1-1/2-in. (38-mm) hydraulic line at an appropriate distance. Figure A1 shows the location of the anode. The life of the 1-in. (25-mm) diameter anode was shorter than that of the gate anode, but this did not create any problems since visual inspection and replacement was simple.

Data and Design Considerations

1. Water Resistivity of the Dalles Pool: Variable (7500 to 9500 ohm-cm) depending on the season of the year.

2. Required Current Density:

a. For bare steel in medium resistivity freshwater, the required current density was 2 mA/sq ft (22 mA/m²).[22]

b. The average current requirement for bare steel in freshwater was approximately 5 mA/sq ft (54 mA/m²).[23] The water turbulence makes this figure reasonable.

c. From experiments conducted at McNary Dam, it was determined that 2 to 2.5 mA/sq ft (22 to 26 mA/m²) are required to polarize 410 alloy steel.

[21] *Electrical Design, Corrosion Control*, TM 5-811-4 (Department of the Army, 1 August 1962); *Design Considerations and Data for the Installation of Cathodic Protection of the Dalles Project Powerhouse Intake Gates*, Report No. 3-201 (North Pacific Division, 1973).

[22] Rock Island District Corrosion Mitigation Course Notes (U.S. Army Corps of Engineers Rock Island District).

[23] *Electrical Design, Corrosion Control*, TM 5-811-4 (Department of the Army, 1 August 1962).

d. The maximum current required to protect a well-painted submerged area was 0.5 mA/sq ft (5 mA/m^2). Since the paint coatings on the hydraulic piping in the gate slots and the support beams were expected to be in relatively poor condition by the time the cathodic protection installation was made, the amount of current leakage to adjacent structural steel was unknown. Therefore, it was decided to design for 2 mA/sq ft (22 mA/m^2) of area.

3. Measured Current Drain: The drain from magnesium anodes in the Dalles Pool was measured at 10.6 mA/sq ft (114 mA/m^2).

4. Efficiency: Anode efficiency vs current drain curves for 3000/5000 ohm-cm resistivity tap water indicated that the efficiency of magnesium was approximately 400 A-hours/lb (880 A-hours/kg). Therefore, for the measured resistivity and current drain, an efficiency of 400 A-hours/lb (880 A-hours/kg) of magnesium was assumed.[24]

5. Crowding Interference: A reduction of 15 percent of current flow was indicated if the spacing between grouped anodes was greater than the number of anodes used in the group. A reduction of 30 percent current flow for three anodes at 5-ft (1.5-m) spacings was also indicated. Where end anodes were closely grouped and other anodes were separated by a few feet from the end anodes, an efficiency of 80 percent normal current flow was assumed.[25]

Design Computations

Table A2 gives design computations of anode comparisons for intake gates on the John Day Dam; Table A3 and Figure A2 list computations for the area of 410 steel/roller chain; Table A4 lists computations for the area of bare and embedded steel on the gates; Table A5 lists the anode requirements for the end and bottom of the gate; Table A6 lists anode requirements for inaccessible parts of the gate; Table A7 lists anode requirements for chain sectors; Table A8 lists the anode requirements between the two top girders of the gate; and Table A9 lists anode requirements for the hoist cylinder. Figure A3 shows a sketch of the anode mounting on gate ends.

[24] Rock Island District Corrosion Mitigation Course Notes.

[25] TM 5-811-4.

Table A1
Anode Requirements for One Intake Gate (Summary)

Area Considered	Anode Length ft (m)	Number Required	Number of Ends	Total Length ft (m)
Gate ends	47 (14)	5	2	470 (143)
Top chain sector	7 (2)		2	14 (4)
Bottom chain sector	5 (1.5)		2	10 (3)
Gate bottom	21.6 (6.58)			21.6 (6.58)
Bottom-gate girder (lower)	21.6 (6.58)			21.6 (6.58)
Bottom-gate girder (upper)	21.6 (6.58)			21.6 (6.58)
Between two top girders	3 (0.9)	5		15 (4.5)

Total anode length = 573.8 (174.8)

Total anode weight per gate = 48.2 lb/20 ft = 2.41 lb/ft $\times$ 573.8 ft = 1382 lb (626 kg)

Expected life = 14.7 years

SECTION C-C

ANODE – TYPICAL REPRESENTATION

HOIST CYL–U/S EL

VIEW A-A

SECTION B-B

END ELEVATION
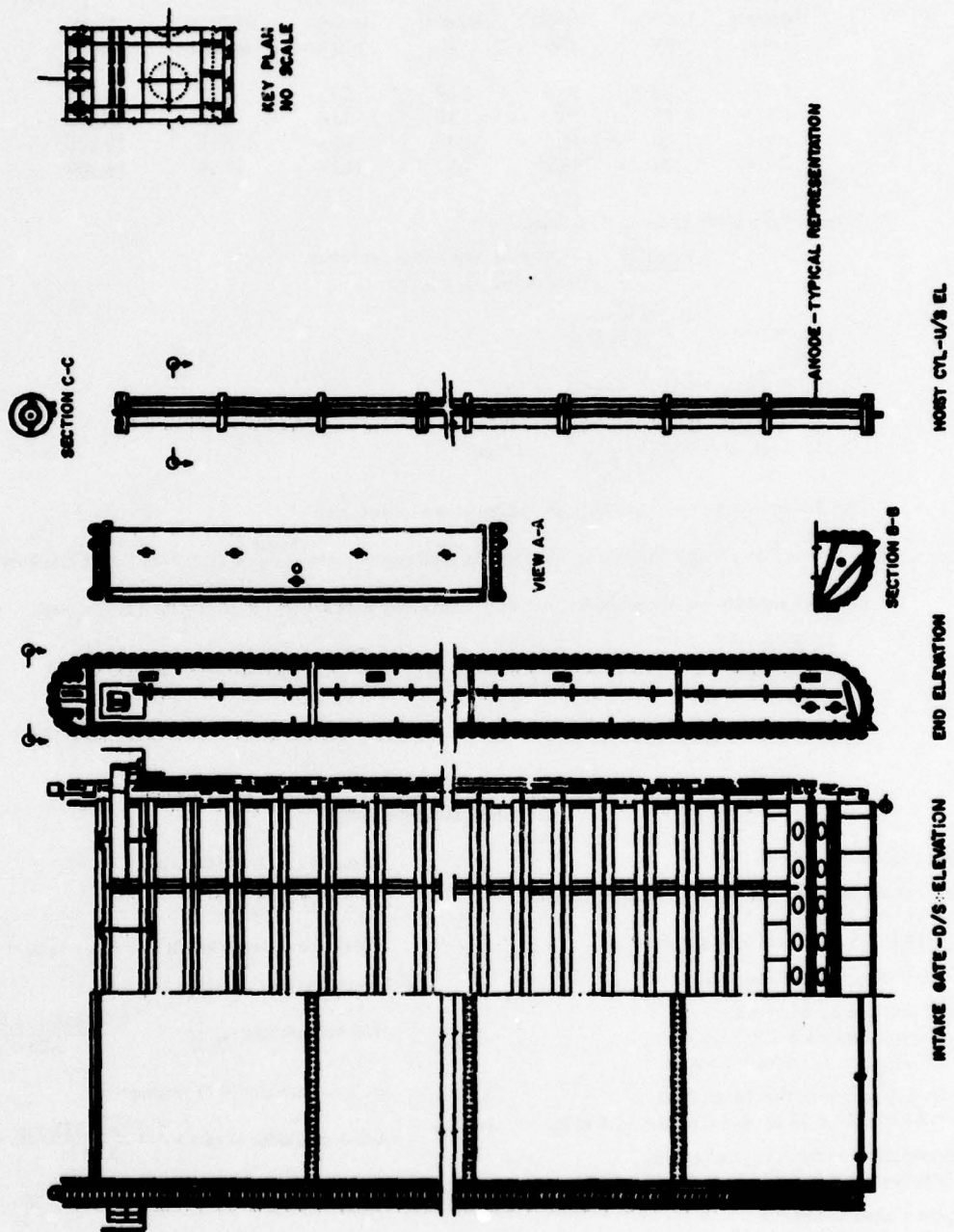
INTAKE GATE–D/S ELEVATION

KEY PLAN
NO SCALE

Figure A1. Intake gate and hoist cylinder.

Table A2
Anode Comparisons*

Magnesium anode output current = 10.6 mA/sq ft (average)

Assumed efficiency of anodes   = 400 A-hours/lb

Anode Diameter (in.)	Anode Length (ft)	Weight (lb)	Weight/ ft	Total mA current output	Sq Ft of Surface	Total A-hours
1.05	20	13.6	0.68	58	5.50	5,440
1.315	20	20	1.10	73	6.89	8,000
1.561	20	30	1.50	85.5	8.16	12,000
2.024	20	48.2	2.41	112.4	10.60	19,300

Expected anode life assuming 75% usage:

$$\text{Life} = \frac{\text{weight lb} \times \text{efficiency A-hours/lb} \times \text{use factor}}{\text{current output, A} \times \text{hr/yr}}$$

$$2.024 \text{ in. anode} = \frac{48.2 \times 400 \times .75}{.1124 \times 8760} = 14.7 \text{ yr}$$

$$1.561 \text{ in. anode} = \frac{30 \times 400 \times .75}{.0855 \times 8760} = 12 \text{ yr}$$

$$1.315 \text{ in. anode} = \frac{20 \times 400 \times .75}{.073 \times 8760} = 9.4 \text{ yr}$$

For the same current requirements, equivalent anode lengths are:

If 20 ft of 2-in. (Nom.) diameter anode meet the requirement, then $\frac{112.4}{85.5} \times 20$ ft = 26.3 ft of 1.561-in.

diameter anode is needed; similarly for 1.315-in. diameter anode, $\frac{112.4}{73} \times 20$ ft = 30.8 are required.

*Metric conversion = 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 sq ft = 0.092 m^2; 1 lb = 0.483 kg.

Table A3
410 Steel/Roller Chain*

Area per roller including two links:

Roller ends (including pin end and link covering end)
= $\pi r^2 = \pi \times$ (2.5 sq in.)
= 19.6 sq in. × 2 ends – 39.2 sq in.

Roller surface = $5\pi d = 25\pi$ = 78.5 sq in.

Outer link area between rollers
= approximately 1/2 × 2-1/2 in.
= 1.25 sq in. × 2 sides = 2.5 sq in.

Outer link area (inside) between links
= 2.5 × 2.5 = 6.25 sq in. × 2 sides = 12.5 sq in.

Exposed roller area not covered by link
= approximately 2.5 sq in. × 2 ends = 5 sq in.

Exposed edges of links
= 2 links × 2 (2-1/2 in. + 5-1/4 in.) × 1/2 in.
= 15.5 sq in.

Exposed pin circumference
= 3/8 in. πd × 2 ends = 3/8π × 1.25 in. × 2
= 2.94 sq in.

Total area of roller & 2 links = 156.1 sq in. = 1.085 sq ft.

Estimated number of rollers per chain =

Top half section = $\frac{\pi r}{5.25} = \pi \times \frac{(20.78 \text{ in.} + 2.5 \text{ in.})}{5.25} = 14$
(approximate)

Bottom gate loop = 11 (estimated)

U/S & D/S sides of gate = $\frac{2 \text{ sides} \times 553.5 \text{ in.}}{5.25 \text{ in.}} = 211$
(approximate)

Total number of rollers per chain = 236

A-1 – Cross section of the stainless steel rollers

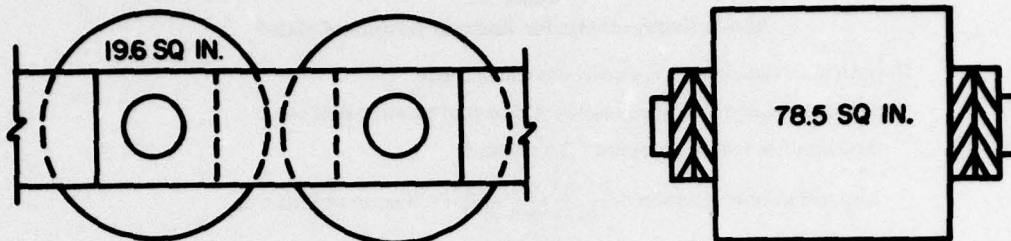*Metric conversions: 1 in. = 25.4 mm; 1 sq in. = 64 mm^2; 1 sq ft = 0.092 m^2.

Figure A2. Roller surface.

Table A4
Bare and Embedded Steel*

Area of 410 steel in gate tracks & guides:

Approximate periphery track length —

$$\text{Bottom sector} = \frac{\pi r}{2} + \frac{\pi r}{2} + 9 \text{ in.} = \left(\frac{27 \text{ in.}}{2} + \frac{6 \text{ in.}}{2}\right)\pi + 9 \text{ in.} = 51.8 \text{ in.}$$

Top sector	$= \pi r$	$= 20.78 \text{ in. } \pi$	$= 65.3$ in.

Intermediate
Lengths $= 553.5 + 552.25$ $= 1105.75$ in.

Approximate track areas = length × width (including rail guides)

Bottom sector $= 51.8 \times 8.5$ in. $=$ 440 sq in.
Top quadrant $= 65.3 \times 8.5$ in. $=$ 555 sq in.
Intermediate D/S $= 553.5 \times 13$ in. $=$ 7,200 sq in.
Intermediate U/S $= 552.25 \times 8$ in. $=$ 4,420 sq in.
Total area of track/gate end $= 12,615$ sq in. $= 87.7$ sq ft

Area of embedded steel:

Track areas as follows —

Downstream side = width × length/12 $=$ sq ft
$= 15.75$ in./12 $\times$ 10 ft $= 13.1$ sq ft
$= 8/12$ in. $\times$ 21 ft $= 14.0$ sq ft
$= 4.5/12$ in. $\times$ 26.5 ft $= 9.9$ sq ft
Upstream side $= 4.5/12$ in. $\times$ 57.5 ft $= 21.6$ sq ft
End guide plate $= 4.5/12$ in. $\times$ 57.5 ft $= 21.6$ sq ft

Total area embedded steel gate end 80.2 sq ft

Grand total of bare 410 steel per gate end (both on gate & embedded) =

256 sq ft chain
87.7 sq ft gate track
80.1 sq ft embedded
423.8 sq ft

In addition to gate ends, the bottom of the gate will require protection
from the embedded stainless steel top seal plate. Area = 14 in./12 × 23 ft
= 26.8 sq ft.

*Metric conversions: 1 in. = 25.4 mm; 1 sq in. = 64 mm^2; 1 sq ft = 0.092 m^2.

Table A5
Anode Requirements for End and Bottom of Gate*

Magnesium anodes required to protect one end of a gate:

Area to be polarized is approximately 425 sq ft of bare 410 steel metal

Amount of current to be applied = 2.5 mA/sq ft

Required number of anodes = $\dfrac{2.5 \text{ mA} \times 425 \text{ sq ft}}{112 \text{ mA} \times .8^{**}}$ = Number of 20-ft rods.

Required number (if 2-in. diameter) = $\dfrac{2.5 \text{ mA} \times 425 \text{ sq ft}}{112 \text{ mA} \times .8}$ = 11.9 (12 or 240 lin ft)

Required number (if 1.56-in. diameter) = $\dfrac{2.5 \text{ mA} \times 425 \text{ sq ft}}{85.5 \text{ mA} \times .8}$ = 15.6 (16 or 320 lin ft)

Required number (if 1.3-in. diameter) = $\dfrac{2.5 \text{ mA} \times 425 \text{ sq ft}}{73 \text{ mA} \times .8}$ = 16.6 (17 or 340 lin ft)

Anode required to protect gate bottom:

Required current = 26.8 sq ft × 2.5 mA/sq ft = 67 mA.

A 1.315-in. diameter anode × 20-in. long would suffice; however, in order to program approximately equal replacement life, a 2-in. diameter anode will be used (full gate width between chains and secured to the downstream side of gate).

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*Metric conversions: 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 sq ft = 0.092 m^2.
**Crowding factor

Table A6
Anode Requirements for Inaccessible Parts of Gate*

Bottom girder anode requirements:

Lower compartment—interior (painted)

Areas		Square Feet
Faring plate—4.25 ft × 21.67	=	92
Flange plate—0.17 ft × 21.67		neglect
Bottom web plate—3.17 ft × 21.67	=	69
Skin plate—2.25 ft × 21.67	=	48
Gussets (11)—$\left(\dfrac{4.25 \text{ ft} \times 1.5 \text{ ft}}{2}\right)$2 sides × 11 =		70
	Total =	279

Amount of magnesium required at 0.5 mA/sq ft
= 0.5 × 279 – 140 mA

Need two 20-ft × 1.315-in. diameter anodes at 73 mA each or a single 20-ft × 2-in. diameter anode which would provide
$\dfrac{140}{121} = \dfrac{0.5}{x}$, ∴ x = $\dfrac{121 \times 0.5}{140}$ = 0.43 mA

Upper compartment—interior:

The areas are approximately equal to the lower compartment.

Use a single 2-in. diameter anode (magnesium) × 21.6 ft long in each compartment.

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*Metric conversions: 1 in. = 25.4 mm; 1 ft = 0.3048 m;
1 sq ft = 0.092 m^2

Table A7
Anode Requirements for Chain Sectors*

Anode requirements at top of chain (180° sector):

Approximate areas of bare metal – square feet

14 rollers $= 14 \times 1.083$ sq ft = 15.2 sq ft

Track area $= \dfrac{65.3 \text{ in.} \times 8.5 \text{ in.}}{144} = \underline{3.8}$ sq ft

Total = 19 sq ft

Anode requirements –

$\dfrac{2.5 \text{ mA/sq ft} \times 19 \text{ sq ft}}{\text{Anode current/sq ft}} = \dfrac{47.5 \text{ mA}}{6.3**} = 7.5$ sq ft

This would require 4-24W anodes (not feasible to mount).

Using 2-in. diameter anodes $= \dfrac{47.5}{10.6} = 4.5$ sq ft

or a length of $\dfrac{4.5}{10.6} \times 20$ in. = 8.5 lin ft

Anode requirements for bottom sector:

Approximate areas of bare metal –

11 rollers $= 1.083 \times 11$ $= 11.9$ sq ft
Track area $= 0.71 \times 4.33$ ft $= \underline{3.1}$ sq ft
Total $= \overline{15}$ sq ft

Anode requirements = 2.5 mA $\times$ 15 = 37.5 mA

Using 2-in. diameter anodes $\dfrac{37.5}{10.6} = 3.5$ sq ft

20 ft $\times$ 3.5 sq ft/10.6 mA/sq ft = 6.6 lin ft required

*Metric Conversions: 1 in. = 25.4 mm; 1 ft = 0.3048 m;
1 sq ft = 0.092 m^2.
**The figure of 6.3 mA/sq ft current output for slab
magnesium is an average based on tests by Portland
District in the Dalles Dam Pool.

Table A8
Anode Requirements Between Two Top Girders

To protect totally enclosed areas into which the dogging beam recesses:

Area – approximately 60 sq ft per side of gate (painted)

Anode requirements – 0.25 mA/sq ft = 0.25 $\times$ 60 = 15 mA

Using a 2-in. diameter anode, 15/10.6 = 1.4 sq ft is required
or $\dfrac{1.4 \times 20 \text{ ft}}{10.6} = 2.6$ lin ft

Protection is also desired in the small center compartment where the stem passes through and in the end compartments where the dogging beams are located.

A 2-in. diameter anode $\times$ 3 ft long – suspended vertically between the two top girders in each of the five compartments was selected.

Table A9
Anode Requirements for Hoist Cylinder

Design based on flood control pool – EL 268.0

Bottom EL of cylinder = approximately 218

Length of cylinder to protect = 50 ft

Length of 1-1/2 in. pipe to protect = 50 ft

Cylinder area $= \pi Dh = \pi \times \dfrac{24.75}{12} \times 50 = 324$ sq ft

Add 5% for flanges – 16 sq ft

Pipe area $= \pi \times \dfrac{1.9}{12} \times 50 = 24.8$ (25)

Total painted area = 365 sq ft

Flange bolts (assumed bare)

3 pair of flanges submerged–twenty 1-5/8-in. diameter bolts

Approximate area $= \left[2.5 \, \pi \times 2 + \left(\dfrac{2.5}{4}\right)^2 \pi \right] \times \dfrac{20 \times 3}{144}$
$= 7.05$ sq ft

Current required for cylinder & pipe = 365 $\times$ 0.25 mA/sq ft
$= 91.3$ mA
Current required for bolts = 7.05 $\times$ 2.5 mA = $\underline{17.6}$
Total Current = $\overline{108.9}$ mA

Using 50 ft of 1-in. diameter anode gives
58 mA/20 in. $\times$ 2.5 lengths = 145 mA
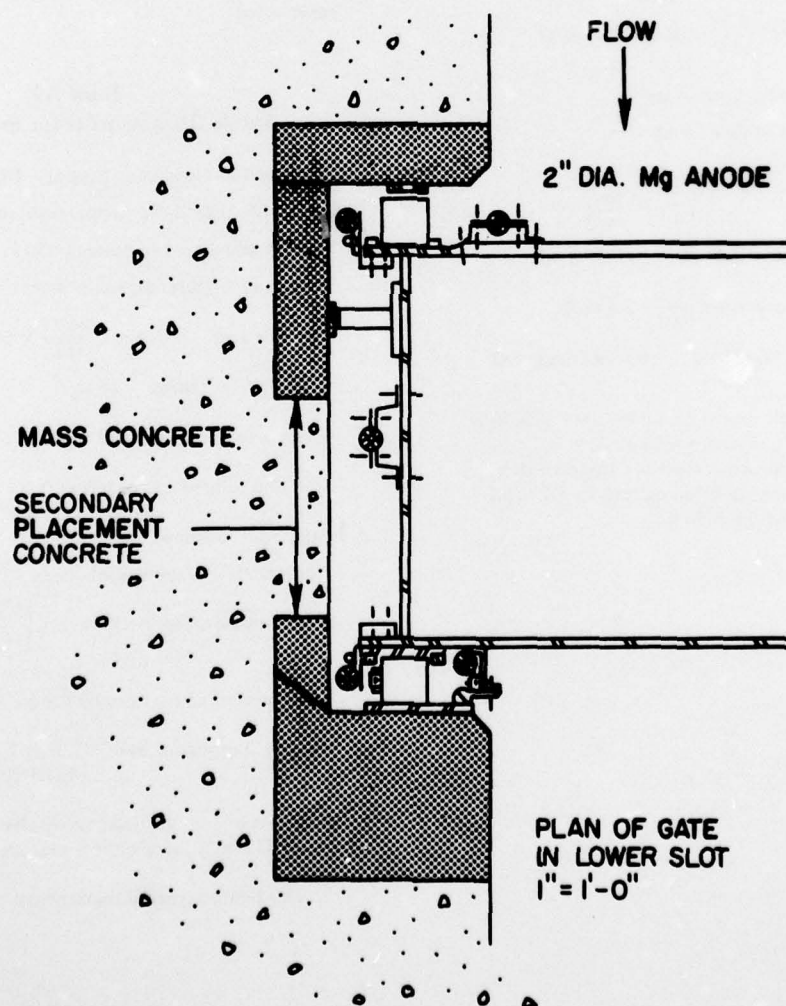
This figure exceeded requirement – which is 108.9 mA.

Figure A3. Location of sacrificial anodes on the gates.

APPENDIX B:
UNIONTOWN LOCK AND DAM
CATHODIC PROTECTION SYSTEM

Description of Installation

The Uniontown Lock and Dam is located on the Ohio River approximately 846 miles (1361 km) below Pittsburgh, PA. The lock system consists of 110-ft (33-m) wide parallel chambers, with nominal lengths of 600 and 1200 ft (182 and 365 m). The upper and lower gates are dimensionally identical, horizontally framed, and approximately 61.5 ft (18.7 m) wide and 54 ft (16 m) high. An impressed-current cathodic protection system was provided for the portions of the gates normally submerged at normal pool steps. The faces inside the lock walls were protected to upper pool stages, even though they were only intermittently subjected to stage above lower pool level.

Details of System

The upstream skinplate of each gate leaf was protected by a grid system of HSCBCI 6-in. (152-mm) diameter button anodes placed in seven vertical rows of four anodes each (Figure B1). One vertical row was along each side of the edge of the skinplate; the remaining five rows were equally spaced between the anodes in this row. Vertical spacing was at the 1/8, 3/8, 5/8, and 7/8 points of the area submerged at normal pool. Spillover from the anodes along the edges protected the quoin and miter girder cells. Each cell in the main structure of the downstream face of each gate (below normal pool) was protected by a single button anode attached to the downstream face of the skinplate at approximately the midpoint of the cell (Figure B2). Each vertical row of upstream anodes was served by a single circuit. Each group of four horizontally adjacent downstream cell anodes was served by a single circuit. For protection, the wire leads for each anode passed through the girders in conduit and terminated in a junction box at the top of the gate. From the junction box, a single lead for each group of four anodes extended to a resistor bank in the rectifier cabinet. The resistor board had a bus bar to which the leads were attached through resistors or shunts, as necessary to balance the current flow to each anode group. An analysis of the surface area anticipated to be served by each anode, assuming uniform paint covering, was used to determine the size resistor needed for each anode group. Low resistance "Holloway Shunts" were used for groups needing no added resistance. With either a resistor or a shunt in each circuit, the current to any group of anodes could be measured during field checks using a millivolt meter across the shunt or resistor. This made it unnecessary to open the circuit to

install an ammeter. The system used 16 rectifiers, each serving one gate face. Both rectifiers serving a single gate leaf were mounted in a common cabinet on the lock wall adjacent to the machinery recess. Also included in the cabinet were the resistor board and a transformer. Multiple conductor flexible cables with plug-in connectors spanned the opening between the machinery recess and the top of the gate to conduct DC current to the anodes. The rectifier cabinet was bolted down when in use; however, it was equipped with casters and a handle for easy transportation to high ground during floods. In future installations, permanent locations for rectifier in the control tower should be considered.

List of Materials Used

Anodes—All Gates

1. All anodes were HSCBCI, special-design button anodes 6 in. (152 mm) in diameter.

2. On the upstream face of all gates there were seven groups of four anodes.

3. On the downstream face of the upper gates there were 15 groups of four anodes.

4. On the downstream face of the lower gate there were 12 groups of four anodes.

5. There was a total of 164 groups of 656 anodes.

Rectifiers

All rectifiers are full-wave, air-cooled selenium stacks, 120/208 V, 1 phase, 60 cycle. DC output was adjustable in 36 approximately equal steps (six coarse and six fine taps) between full-rated output and zero. Circuit breaker protection was specified for the AC circuits and either a circuit breaker or fuse was used for the DC circuits. Four hundred-forty volts were used for distribution in the lock power circuits. Since rectifier meters were often read by untrained personnel, maintenance was required under adverse conditions. Therefore, a 440-V rectifier operation was considered undesirable. A 440- to 120-V dry transformer in the rectifier cabinet reduced operating voltage to a safer level. All 440-V circuits were isolated from the normally accessible area. Maximum DC output ratings were:

1. Upper gates of the upstream face—24 V, 8 A.

2. Upper gates of the downstream face—60 V, 42 A.

3. Lower gates of the upstream face—24 V, 8 A.

4. Lower gates of the downstream face—30 V, 16 A.

The total was 16 rectifiers—eight at 8 A, four at 42 A, and four at 16 A.

Quoin End

Miter End
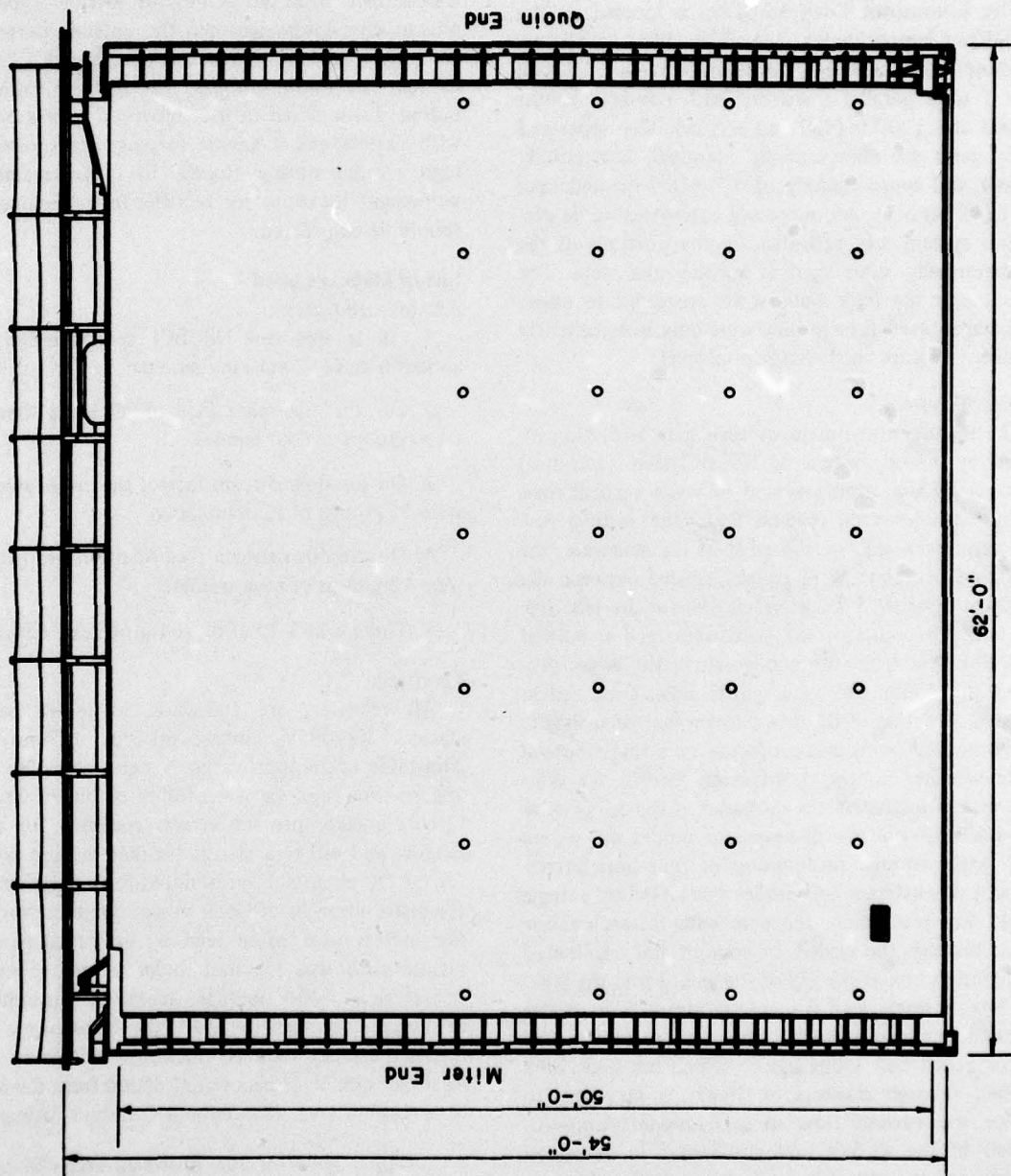
62'-0"

50'-0"

54'-0"

Figure B1. Location of button anodes on upstream side of Uniontown Lock (Louisville District).
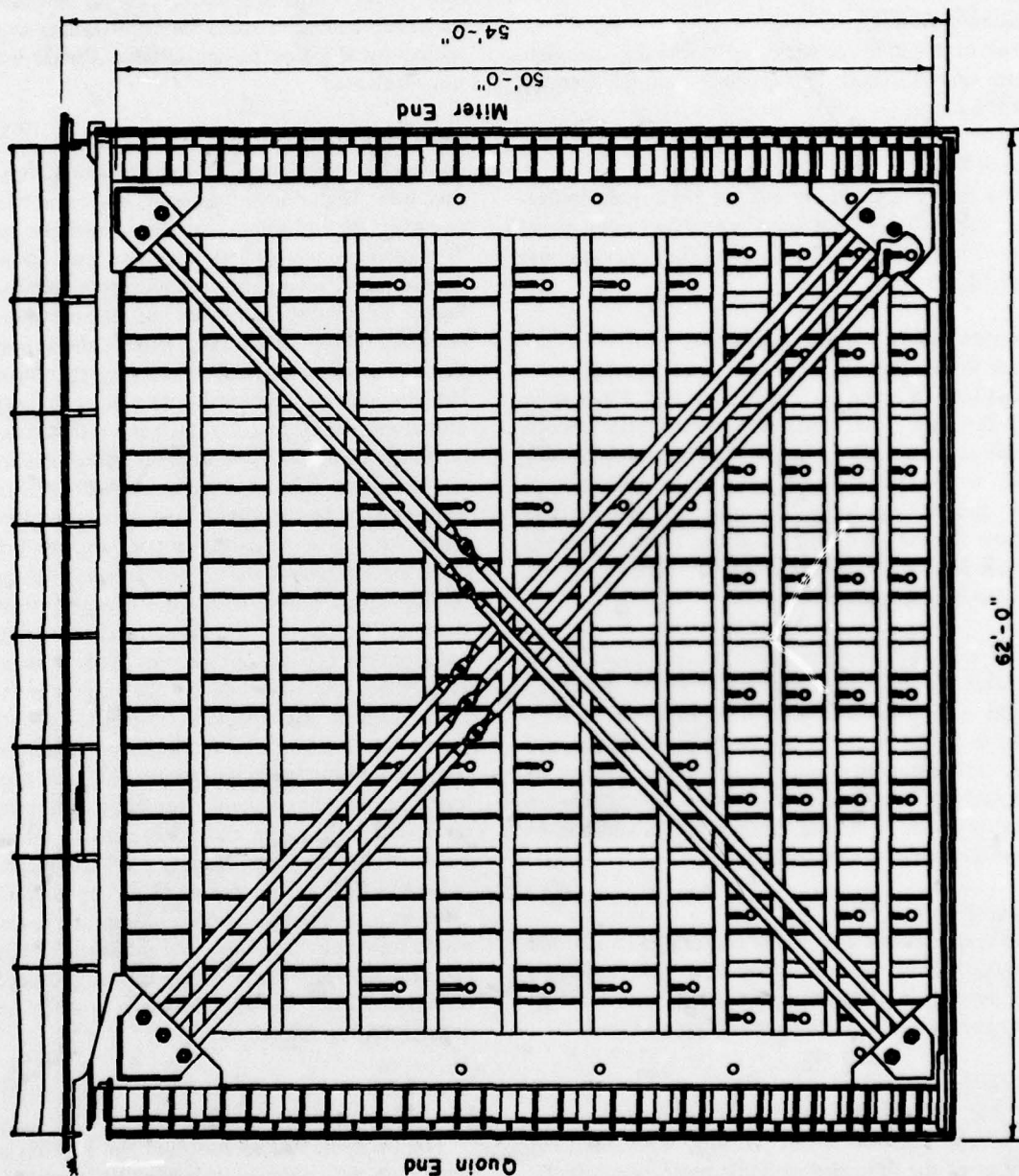
68

Figure B2. Location of button anodes on downstream side of miter gate at Uniontown Lock (Louisville District).

69

Resistor Boards

Each resistor board assembly consisted of two bus bars, with a total of 22 terminal screws, 22 through-panel terminal studs with the necessary resistors and shunts, and one ground terminal. There were eight resistor board assemblies.

Installation Cost

The installation contract cost for the complete system was $130,000. This is one-seventh the cost of a new miter gate.

Type of Paint

The gates were blast cleaned and given three double-spray coats of Vinyl V-766 0 and two double-spray coats of Vinyl V-103. The final dry film thickness was 6 mils (0.15 mm).

Uniontown Lock Cathodic Protection System Specifications

The lock cathodic protection system at Uniontown Lock consisted of rectifiers, anodes, terminal cabinets, and all necessary accessories, including interconnecting cables and conduits. The system was furnished complete and in operating condition. Current-limiting resistors for the lock were furnished (when required) and installed by the Government at the time the system was placed in operation.

The gate cathodic protection system provided all equipment, wiring, and wiring devices necessary to produce a continuous flow of direct current from electrodes in the water electrolyte to the gate surfaces, and to protect adequately and efficiently the surfaces of the metal gates against corrosion where the surfaces are in contact with water; this system was in addition to the protective coating on the gates.

Electrical Work

All materials and equipment conformed to contract documents and were in accordance with approved recommendations of the manufacturer. The installation was done by workmen skilled in this type of work.

Detail Drawings

Within 120 days after receipt of notice to proceed, and before commencement of any work, detailed drawings of the proposed cathodic protection installation were submitted in sextuplicate for approval. The drawings provided dimensions and showed anode arrangement for both elevated and sectional views of the gate, rectifier details, and locations, mounting details, wiring diagrams, and any other pertinent information

considered necessary for the proper installation and performance of the system.

Approval of Materials and Equipment

The contractor submitted for approval a complete list, in triplicate, of materials and equipment to be incorporated into the work. The list included cuts, diagrams, and such other descriptive data as was required by the Contracting Officer. Partial lists were not considered.

Lock Gate Anodes

Anodes were 6-in. (152-mm) diameter high-silicon cast iron. High-silicon, cast-iron, button anodes were cast of an alloy of silicon, carbon, manganese, and iron. The silicon content was not less than 14 percent. Anodes were suitable for cathodic protection use, were highly resistant to corrosion, and demonstrated good electrical properties. Anodes were of the approximate size and shape indicated on the project drawings and had the indicated terminal connections and mounting provisions. Anodes were located and installed as shown on the drawings. Polychloroprene gasket material was not less than 1/16-in. (0.06-mm) thick. Plastic plugs were molded or fabricated from an approved polystyrene. After assembly, the anode support bolt was completely insulated on the button side of the gate by forcing epoxy cement through a passage provided for that purpose, around the insulating sleeve (filling the bolt-head cavity), and out the vent cavity in such a way as to place the vent hold at the highest point. The epoxy cement had a suitable dielectric strength, was water resistant, and did not generate enough heat to damage or react with the plastic plug, the insulating bushings, or the gaskets. Insulating bushings were fabricated from nylon and conformed to the requirements of the American Society for Testing and Materials (ASTM) Standard D 789-73.[26] The surface of the gates was covered by the polychloroprene gasket. The anode was shot-blasted to clean the metal to provide a bonding surface for the epoxy cement. Anodes were installed before painting and were properly masked during painting operations.

Lock Cable
Direct Current Cable

The DC cable was seven-strand No. 8, AWG copper conductor, with polyvinylchloride (PVC) insulation for 600-V service. The cable conformed to the applicable

[26] *Nylon Injection Molding and Extrusion Materials,* ASTM Standard D 798-73 (American Society for Testing and Materials [ASTM], 1973).

requirements of Federal Specification J-C-30.[27] The cable was resistant to electroendosmosis, moisture absorption, oxygen, sunlight, oils, greases, gasoline, acids, alkalis, and other chemicals, and was suitable for direct immersion in river water. Each anode lead was continuous; i.e., there were no splices from its point of connection to the anode or to the terminal cabinet mounted on the gate structure. Flexible cable connections between the terminal cabinets and the lock wall outlets and between the lock wall outlets and the rectifier DC terminals were made with two conductor No. 10, flexible portable power cable, Underwriters' Laboratory, Inc. (UL), Type "SO." Anode leads were marked with the anode number at the point of connection to the terminal board.

Alternating Current Cable

Flexible cable connections between the AC power outlets in the lock walls and the AC input terminals of the rectifiers were made with three conductor No. 10 AWG, flexible portable power cable, UL Type "SO."

Rectifier
General

Rectifiers were adequately housed in metal cabinets with doors arranged for padlocking, were suitable for outdoor installation, and were of such dimensions and construction as to be conveniently portable across the walkways atop the lock gate structures. Rectifiers were furnished in accordance with project requirements.

Cabinets

Cabinets were constructed of sheet aluminum not lighter than No. 12 gage; appropriate structural shapes were used. The cabinets had hinged plain doors and could be padlocked. All ventilating openings were covered with an aluminum insect screen. Cabinet wheels were designed to support at least three times the weight of the complete rectifier unit. Studs for the cabinet clamp (used to secure the rectifier to the pipe rail) were welded to a reinforced back section of the cabinet at the factory before finishing.

Control and Instrument Panel

The control and instrument panel was the dead-front type; its primary connection terminals were protected by a removable metal or molded plastic cover.

Circuitry

Rectifiers were full-wave and of the bridge type; each rectifier cabinet contained one double-winding rectifier transformer with secondary taps, a rectifier stack, and appropriate meters and accessories. The rectifiers terminated in one pair of DC output terminals. Rectifier components were interconnected.

Circuit Breakers

The rectifier-transformer primary circuit was 120/240-V, 5000-A interrupting capacity, double-pole, and had a molded-case circuit breaker which could be used to disconnect both conductors. The breaker had instantaneous and inverse time trips suitable to the design load. Circuit breakers conformed to Federal Specification W-C-375B/GEN, Class 11b.[28]

Rectifier Transformers

The rectifier transformer was a double-winding, air-cooled (without fan), single phase dry type, with a primary operating voltage of 120 V, single phase. The transformer conformed to National Electrical Manufacturer's Association (NEMA) Standards.[29] The transformer secondary had "coarse" and "fine" taps sufficient to permit variations of the DC output voltage in increments of approximately 0.5 V, i.e., from zero to the maximum rated voltage. All transformers received at least three coats of moisture-proof varnish.

Voltage Selection

Transformer taps were brought to back- or panel-mounted tap switches with indicator knobs on the front of the panel.

Rectifier Stacks

Rectifier stacks were solenium cells and had enough units to provide full-wave, bridge-type rectification within the manufacturer's ratings. The rectifier was also suitable for operation over an ambient temperature range of 0 to 110°F (−17 to 43°C).

Meters

An ammeter and voltmeter of standard manufacture with a semiflush 3-1/2 in. (89 mm) round or rectangular panelboard was provided in the DC circuit. The instruments had a guaranteed accuracy of 0.5 percent of full-scale reading, zero adjustment, and a minimum

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[27] *Cable and Wire, Electrical (Power, Fixed Installation),* Federal Specification J-C-30A and Am-1 (9 December 1974)

[28] *Circuit Breakers, Molded Case; Branch Circuit and Service,* Federal Specification W-C-375B, Class 11b.

[29] *Standard for Specialty Transformers* (National Electrical Manufacturer's Association [NEMA]).

scale length of 2.4 in. (60 mm). Scale ranges were 5 A and 10 V. Full-load reading was indicated by a red mark on the meter scale. Each meter had a momentary contact switch—either integral with the meter or separately mounted—for momentary reading.

Overload Protection

The DC output circuit had a panel-mounted fuse large enough to protect the rectifier. Two sets of spare fuses were mounted in spare fuse clips inside the rectifier cabinet door.

Convenience Receptacle

Each rectifier unit had a panel-mounted, grounding-type 120-V, 15-A convenience receptacle connected to the 120 V circuit.

Lock Gate Terminal Cabinets

The terminal cabinets were NEMA Type 3 and were raintight and weather resistant. They were made of 16 gage galvanized steel and finished in the manufacturer's standard enamel finish. All cabinets were large enough to accommodate the necessary standard screw terminal blocks and wiring. All conductors were identified in the cabinet by plastic or metal tags, or plastic sleeves indicating the anode number. The cabinets were securely mounted on the gate structure; the removable front faced the walkway. Jumper connections were installed in each lead in the terminal cabinets. The contractor provided and installed screw terminal blocks and jumper cables.

Wiring on Gate Structure
General

All anode lead wiring on the gate structures were either exposed or in nonmetallic conduit. Each anode had enough lead length (without splice) to reach the terminal cabinet. No splices were permitted. Watertight bushings were installed at all points at which the cable penetrated a watertight member. Watertight insulating bushings had a cable-sealing fitting which made a watertight conduit connection and a watertight seal between the cable jacket (or insulation) and the fitting. At all locations at which a conduit penetrated a watertight member, a watertight packing gland was installed. The cable and anode were factory constructed by the manufacturer of the anode.

Conduit and Fittings

Nonmetallic Conduit. The nonmetallic conduit was Type 40, heavy-wall PVC rigid-plastic conduit and conformed to the requirements of NEMA TC-2.[30]

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[30] *Electrical Plastic Tubing (EPT) and Conduit, EPC-40 and EPC-80, TC 2-1975 (NEMA, 1975).*

Conduit Fittings and Outlets for Nonmetallic Conduit. Fittings and outlets were molded from the same material as the conduit they were used with and were products of the conduit manufacturer. Fittings and outlets were solvent welded to the conduit using the solvent recommended by the manufacturer. All fittings conformed to the requirements of NEMA TC-2.[31]

Marking
General

Marking, where required, was done with stamped or engraved metal or plastic plates or plastic sleeves.

Rectifier Cabinets

Rectifier cabinets were identified by stainless steel plates attached to the outside of the rectifier cabinet with bolts or screws.

Rectifier Instrument Panel

Tap Switches. Tap switches were identified by plastic plates denoted as "coarse" and "fine." Individual tap positions were identified by the letters "A," "B," and "C," etc., and numerals "1," "2," "3," etc., respectively.

DC Output Terminals. Rectifier DC output terminals were identified by plastic plates indicating the polarity of the terminal and point of connection to the system, i.e., "+ANODES" and "−STRUCTURE."

Anode Cable Leads

Anode cable leads were identified at the resistor and terminal cabinet by plastic sleeves or tags showing the anode lead number.

Primary Connections

Primary connections to the rectifier were made by a panel-mounted, covered terminal block with screw connections.

Special Tools

The contractor furnished a complete set of special tools for use in installing all the anodes. Tools used in making the original installation, provided they were in good working condition, were considered acceptable.

Lock Spare Parts

The contractor furnished spare anodes and installation components of each type used in the original installation equal to 5 percent of the total of each size

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[31] *Electrical Plastic Tubing and Conduit.*

and type. Sufficient polychloroprene sheeting, mounting hardware, and epoxy cement were also furnished for the installation of HSCBCI button anodes.

Instruction Books

Three complete instruction books containing complete information on the assembly, operation, adjustment, maintenance and repair of the equipment, together with detailed circuit diagrams, block diagram, parts lists, drawings, and photographs were furnished by the contractor.

Repair of Existing Work

The work was carefully laid out in advance, particularly where cutting, channeling, chasing, or drilling of floors, walls, partitions, ceilings, or other surfaces were necessary for the proper installation, support, or anchorage of the conduit, raceways, or other electrical work. Any damage to building, piping, or equipment was repaired by skilled mechanics at no additional cost to the Government.

Tests

After the lock cathodic protection system was completed, the contractor conducted operating tests on each of the lock gate systems. Each rectifier was energized and the voltage at the DC bus in the terminal cabinets was measured and recorded on the lowest and middle positions of the tap switches. (Note: the rectifier "+" terminal was connected to the "+" bus, and the rectifier "−" terminal was connected to the gate structure.) Each anode lead was tested to assure that all anode leads were free of short circuits to the gate structure. Any failures of the lead and anode isolation were corrected by the contractor and proof-tested at no additional cost to the Government; the tests were performed at no additional cost to the Government. All tests were performed in the presence of the Contracting Officer or some other authorized representative. The contractor furnished all instruments, personnel, and power required for the tests. After testings, the systems were de-energized by the contractor. Final adjustments and installation of current-limiting resistors, when required, were made by the Government.

Guarantee

Materials, equipment, and workmanship were guaranteed for 1 year from the date of acceptance (either for beneficial use or final acceptance). Upon receipt of notice from the Government of failure of any part of the guaranteed equipment material or workmanship during the guarantee period, the affected part or parts were replaced promptly with new parts, by, and at the expense of, the contractor. The contractor acknowledged responsibility under these guarantee provisions by letter, stating the equipment, materials, and workmanship referred therein were guaranteed and the inclusive dates of the guarantee period.

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